



United States
Department
of Agriculture

Forest Service

**Rocky Mountain
Research Station**

Proceedings
RMRS-P-7

March 1999



Rio Grande Ecosystems: Linking Land, Water, and People

Toward a Sustainable Future for the Middle Rio Grande Basin



Abstract

Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey, F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 245 p.

These proceedings are an outcome of a symposium and workshop held June 2-5, 1998 in Albuquerque, NM. Hosted by the USDA Forest Service, Rocky Mountain Research Station and the U.S. Fish and Wildlife Service's Bosque Improvement Group, in collaboration with numerous partners from a variety of sectors, the symposium was designed to report on current research and development activities in the Middle Rio Grande Basin. The purpose of the meeting was to share information and develop ideas for sustaining and conserving Middle Rio Grande Basin ecosystems, especially those from Cochiti Dam to Elephant Butte Reservoir. Experts were invited to contribute oral presentations, posters, and papers that addressed five Basin themes. Theme one's session was designed to identify methods and opportunities to enhance communication and collaboration among researchers, managers, and communities. A second theme explored ideas and approaches for conserving water and riparian resources in relation to human needs and population growth. Theme three discussed how watershed processes form linkages and influence management of upland and river resources. A fourth session identified methods and strategies for restoring and monitoring basin ecosystems and discussed project successes and failures. Theme five reported on status of endangered and sensitive species, biological diversity, and opportunities for restoring and managing habitats to recover species. Management and understanding of the Middle Rio Grande Basin's natural resources and ecosystems require communication and cooperation of partners across cultural, landowner, and organizational boundaries. To produce a shared understanding of the current state and desired future state of the Middle Rio Grande Basin and to outline the steps needed to move toward the desired future, a facilitated workshop was held the last day of the conference. The results of this workshop are reported in the concluding section of this proceedings. The technical coordinators of the symposium and proceedings wish to acknowledge all the partners who have contributed to the research, restoration, technology development, educational outreach, and special events and activities designed to improve human and ecosystem conditions in the Basin. We hope this volume captures at least some of the excitement, ideas, and productivity generated by Basin projects over the past several years.

Key words: Rio Grande Basin, conservation, watershed, endangered species, sensitive species, restoration

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Rio Grande Ecosystems: Linking Land, Water, and People

Toward a Sustainable Future for the Middle Rio Grande Basin

**June 2-5, 1998
Albuquerque, New Mexico**

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Introduction



**People, Culture, and
Communication**



**River and Riparian
Issues**



Watershed Issues



**Restoration and
Monitoring Issues**



**Biodiversity and
Endangered Species**



Workshop Summary



Introduction



Rio Grande Ecosystems: Proceedings Introduction

Deborah M. Finch
Jeffrey C. Whitney

These proceedings are an outcome of a symposium and workshop of the same title held June 2-5, 1998, in Albuquerque, New Mexico. Hosted by the USDA Forest Service, Rocky Mountain Research Station and the U.S. Fish and Wildlife Service's Bosque Improvement Group, in collaboration with partners from a variety of public and private sectors, the symposium was designed to report on current research, development, and educational activities in the Middle Rio Grande Basin. Participants shared information and developed ideas for sustaining and conserving Middle Rio Grande Basin ecosystems, especially those from Cochiti Dam to Elephant Butte Reservoir.

In 1994, the Rocky Mountain Research Station in Albuquerque developed and implemented a 5-year research program to evaluate ecological conditions of Middle Rio Grande Basin ecosystems. This Forest Service Research program addressed four problem areas: (1) ecology and restoration of upland basin ecosystems, (2) watershed analysis and stream quality, (3) riparian habitats and species, and (4) human history and culture. More than 25 cooperating organizations have been participating in this program, either by conducting research through contracts and agreements, by matching funds and sponsoring new research, or by cooperating through various land use agreements. Simultaneously, the U.S. Fish and Wildlife Service developed a program of research, monitoring, management, and education focusing on improving ecological conditions and communications along the Middle Rio Grande. This program, implemented through the Bosque Improvement Group, was also initiated as a 5-year effort. Combined, both programs have sponsored over \$1 million per year of Rio Grande Basin activities from 1994 to 1998. This includes cost-share and matching dollars contributed by collaborating organizations such as Bureau of Reclamation, U.S. Geological Survey, Army Corps of Engineers, State of New Mexico, City of Albuquerque, National Forests, National Wildlife Refuges, University of New Mexico, and several other universities, private institutions, environmental organizations, and public agencies.

Specially designated funds allocated to these two programs have been used to develop partnerships, conduct research, and expand knowledge for managing the Rio

Grande and its associated natural resources and ecosystems. After prioritizing, sponsoring, and conducting projects for the past 5 years, we have convened this symposium to report relevant results, describe progress, and document outcomes of joint ventures. The research results, technology, and partnerships described in these proceedings attest to the many achievements and products these programs have helped to generate in the Basin. Viewed by some as the "river of life," the Rio Grande's past, present, and future are captured in this volume. Success stories are worth telling and worth reading about.

We invited experts to contribute oral presentations, posters, and papers that addressed five Basin themes. Theme One's session was designed to identify methods and opportunities to enhance communication and collaboration among researchers, managers, cultural groups, and communities. Historical overviews from different cultural perspectives were presented that helped to lay the groundwork and direction for communication about current environmental conditions, conflicts, and options. Theme Two participants explored ideas and approaches for conserving water and riparian resources in relation to human needs and population growth. Theme Three focussed on how watershed processes form linkages and influence management of upland and river resources. Theme Four participants identified methods and strategies for restoring and monitoring basin ecosystems and discussed project successes and failures. Theme Five was a report on the status of endangered and sensitive species, biological diversity, and opportunities for restoring and managing habitats to recover species. The written papers that resulted from the symposium are grouped along similar lines.

An evening poster session and social was held at the Albuquerque Aquarium. Symposium participants, accompanied by friends and family members, viewed scientific posters, chatted with presenters, toured exhibits of sea life, and exchanged ideas and information with strolling colleagues. Poster papers were assigned to theme categories using an ad-hoc basis.

Management and understanding of the Middle Rio Grande Basin's natural resources and ecosystems require communication and cooperation of partners across cultural, land-owner, and organizational boundaries. To produce a shared understanding of the current state and desired future state of the Middle Rio Grande Basin and to outline the steps needed to move toward the desired future, a facilitated workshop was held the last day of the conference. The workshop was designed to enable participants to plan some joint actions for improving environmental conditions in the Rio Grande watershed and river corridor and at the same time learn a new way to increase their success rate in

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achieving goals when working together. Participants were first asked to find areas of “common ground” regarding their desired future of the Rio Grande Basin. Then they were asked to examine their views of the current status of the Basin so as to be able to determine what the appropriate actions would be. During these exercises we saw a positive release of “structural tension,” a phenomenon defined by Workshop Facilitator, Dr. Barbara Coe of Daystar Associates, as energy that generates action toward the goal. The written results of this workshop are reported in the concluding section of this proceedings. Additional outcomes included: (1) increased understanding of the similarities and differences in participants’ desires for the future of the Rio Grande, (2) increased understanding of the current state of

the Rio Grande Basin, (3) preliminary action plans for elements of the desired future, and (4) increased knowledge of a new way to achieve goals collaboratively.

In conclusion, the technical coordinators of the symposium and proceedings wish to acknowledge all the partners who have contributed to the research, restoration, technology development, educational outreach, and special activities designed to better human and ecosystem conditions in the Basin. A comprehensive list of those organizations that helped to make this symposium successful is included in the beginning of the proceedings. We hope this volume captures at least some of the excitement, ideas, and productivity generated by Basin projects over the past 5 years.

People, Culture, and Communication



Rio Grande Basin and the Modern World: Understanding Scale and Context

Joseph A. Tainter

Abstract—Environmental problems are social issues, embedded in economic and political contexts at the local, regional, national, and global levels. Placing environmental issues on the scale from local to global clarifies conflicts between the level at which problems originate and the level at which they must be addressed. Local issues today often originate in sources distant in time and space, increasing the difficulty of discerning and addressing them. Conflicts in environmental management can be approached by understanding their broader context and the appropriate level at which to manage them.

Scaling and Social Context

Environmental problems are really social issues. Environmental matters do not exist on an independent plane in the biophysical world. Ecosystems, being systems, adjust automatically to what we call disturbances, and cannot care about such matters as species composition, ground cover, or water flow. An environmental phenomenon becomes a problem only because people perceive it to be. Variation in human perception gives rise to environmental concerns, the research by which we comprehend them, and the confrontations or negotiations by which we resolve them.

To understand that environmental problems are really social issues is also to understand that they have scalability that is characteristically fractal. As we consider environmental issues ranging from local to national to global, we find that the problems fundamentally retain the same form, the same parts, and the same relations among parts. Always, for example, there is conflict between immediate human livelihood and long-term environmental resiliency. The fact that the problematical relationship between humanity and the environment tends to repeat the same patterns and issues helps us to develop a context to understand both what we experience in the Rio Grande Basin today and the broader processes in which we participate. A perspective that is comparative and historical helps to clarify both the situation of the Rio Grande Basin and the meaning of the ecosystem approach to management. The discussion is far-ranging, and is meant to illustrate the diversity of the knowledge that we need to understand any region today.

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The era since World War II has been particularly transformative in many places, of which it is useful to relate one example. Until World War II communities in this area were relatively isolated and closed. Within a community everyone knew everyone else, the information pool was homogeneous, and decision-making was primarily consensual. There were few differences among people, either technical, social, or economic. The system of land use had been in operation for a very long time. People knew the area intimately, and their subsistence practices were suitable to the environment and sustainable over the long term.

Roads were introduced in the period just after the war, leading to increased contact between villages and with the outside world. This brought new influences and information about the world at large, and new opportunities and ways of doing things. Within villages both the pool of information and community organization began to differentiate. Villages lost some autonomy as they came to be embedded in larger systems at the regional and national levels. As urban ways of living penetrated the countryside, people began to acquire manufactured goods and cash became increasingly important.

The last 50 years have seen much emigration from the villages, as people have moved to the outside world to find work. Social and economic differentiation accelerated, so that no longer could everyone know everything about everyone else. Personal and group interests began to conflict. Subsistence practices changed also. Transformations in cattle grazing meant that fire stopped being used to keep upland pastures clear of competing vegetation. This led to an overgrowth of undesirable woody plants and to erosion.

The natural environment, and how it is used, have been central to the people's cultural heritage. Yet forests in the region are now controlled by the government, and there is frequent conflict between forestry officials and local residents. Organizations external to the area now promote projects to develop the local economy. The great beauty of the area is to be marketed by far-off urban residents to other urban residents. These outsiders bring an ethos in which heritage is to be preserved rather than lived. Forests are to be maintained largely for urban values. The architectural style is to be preserved even though local people can no longer afford it, and no longer have free access to raw materials in the forests.

As local self-sufficiency declined, the region has become more and more dependent on the commercial economy and the government. Today many people, particularly older ones, are supported by government payments. Being embedded in larger systems means that the transformation from autonomy and self-sufficiency to dependency and environmental deterioration is probably irreversible in the near future (Green and others 1998, van der Leeuw and others n.d.).

This is a description of changes, not within the Rio Grande Basin (though it could almost be), but in the region of Epirus in the northwest of Greece. We recognize the account and respond to it because, with a few changes in minor details, it could easily describe what has happened in the Basin over the past 50 years. How is it that two distant and unrelated places could exhibit such strikingly parallel developments?

The answer lies in understanding the scalability of economic and environmental change. The description of Epirus sounds not only like the Rio Grande Basin, but also like many other places that have been transformed in recent decades. These places tend to change along parallel courses because they have become embedded in a global economic system in which participation is rarely optional. To a degree that is generally not understood this system guides the development of localities that were previously unconnected. Places like the Rio Grande Basin or Epirus, once largely autonomous and self-sufficient, may never again control their own destinies.

Social Memory, Hierarchy, and Heterarchy

Epirus exemplifies the problem of scaling in environmental management. The problem concerns the levels at which environmental problems arise, and the levels at which we consider and devise solutions to them. Often these levels exist in blissful ignorance of each other. Take climate change as an example. The Intergovernmental Panel on Climate Change (IPCC) periodically issues reports synthesizing scientific information on this topic. Its most recent report in 1995 was in three volumes, one of which concerned the social and economic dimensions of climate change (Bruce, Lee, and Haites 1995). It is a remarkable compilation, which addresses such pressing matters as adaptation and responses, equity, decision-making frameworks, and economic considerations. Yet within its learned chapters one looks fruitlessly for discussions of scaling, or for sensitivity to the matter, or even, at the very least, for awareness of it.

Scaling in this case concerns the level at which humans respond to environmental change, or attempt to manage it. As befits an organization chartered by the United Nations, IPCC considers adaptation and responses primarily at the level of nations, and within nations, at the level of cities. Discussions of equity, for example, usually turn on relations of developed nations to those in transition. Adaptation is discussed in terms of responses that *nations* might undertake, such as steps to protect coastlines and low-lying areas. Certainly these matters are important, but they are not the considerations of most people who will be affected by climatic or other environmental change. The major part of humanity's adaptation will come at the local level, at a community or regional scale, among people who do not participate in international deliberations and who know nothing of such concepts as international or intergenerational equity, opportunity costs, return on investment, or net present value.

Environmental responses at the local or regional level, including the Rio Grande Basin, reflect the accumulated knowledge of people who have occupied a territory for generations, and who have learned through long experience

how to respond to change (McIntosh, Tainter, and McIntosh n.d.). Environmental responses at this level are based on knowledge of which national governments, and international organizations such as IPCC, are typically unaware. Carole Crumley, for example, has studied traditional farming and gardening practices in the Burgundian region of France (Crumley n.d.). Millennia of experience with local conditions have given these people knowledge to farm sustainably. Yet as the French government accedes to international demands for open markets, local production systems are being destroyed. The result for the French government is tractor parades of angry farmers through Paris. In Burgundy the consequences are more serious: to compete in international markets these farmers must expand their scale of production. Hedgerows are being destroyed to allow for larger fields, and centuries-old conservation practices are being abandoned. Closer to home, similar problems generated by the North American Free Trade Agreement have damaged subsistence farmers in southern Mexico, and contributed to the grievances fueling the rebellion in Chiapas. Meanwhile, in the Rio Grande Basin, we seem increasingly to worry about farmland preservation less as a fundamental aspect of our lives, and more as a quaint curiosity, part of our conception of a picturesque landscape.

In a world that has become globally interconnected we will increasingly experience conflict between action at the local level and actions at higher levels. Environmental action at the local level, among people who have occupied a region for much time, is initiated on the basis of what has been termed *social memory* (McIntosh, Tainter, and McIntosh n.d.). Social memory is the mechanism by which local-level societies retain, transmit, and modify knowledge of the environment, its past changes, and successful responses to those changes. Social memory is encoded in the very things that form the basis of life in small communities: cosmology, myths, rituals, stories, and drama. Social memory is active in all communities, even those that are part of nations with scientific traditions. The Burgundians studied by Carole Crumley (n.d.), for example, encode knowledge of environmental variation in sayings and aphorisms that guide how they prepare and tend vegetable gardens. Gardening in turn serves as a repository of knowledge and experience about broader environmental variation. On the other side of the world, China possess perhaps the oldest continuous tradition of social memory (Hsu n.d.). Proverbs predict how one state of weather leads to another, while pragmatic observations on the environment are encoded in poems and songs. These traditions have been transmitted for centuries. The people of the Rio Grande Basin have had a similarly rich tradition of environmental knowledge, extending over a century in the case of Anglo-Americans, for several centuries among Hispanos, Apaches, and Navajos, and even longer among Puebloans.

A physical remnant of this tradition can be found south of Tijeras Canyon, along an old state highway that runs parallel to but largely hidden from the current road. It was a narrow, curving road, meant to be driven at slow speeds. Amidst rock art of the 14th century there is a sign from earlier this century, hand painted on a limestone cliff. It advertises, in a characteristically New Mexican combination of Spanish and English, that "Curandera cures all." Whoever this *curandera* was, she carried a long tradition

about the medicinal use of local plants. It is an example of what we call social memory. Her tradition still exists, though many New Mexicans, newly arrived and working for some modern institution, will be unaware of it. It is a tradition that can no longer galvanize social action to the extent that it once did.

Responses to environmental challenges can be categorized by the channels through which they are initiated. In broad terms these channels can be termed *hierarchical* and *heterarchical*. The meaning of hierarchy is widely understood. In a social context it refers to people or institutions that are ranked relative to each other, and connotes authority and power. Heterarchy, a term coined by Carole Crumley (1979: 144), means just the opposite: a social condition in which people or institutions are unranked relative to each other, or can be situationally ranked in a number of ways. Of course most societies today incorporate elements of both hierarchy and heterarchy. The communities of central and northern New Mexico in the 18th century could be viewed as a heterarchy, but they were in turn linked hierarchically through Santa Fe to the government in Mexico City, and ultimately to the Spanish Crown. The villages of Epirus in the 1930s similarly formed a local heterarchy, linked weakly to the national government in Athens.

Hierarchy and heterarchy differ in the speed and scale at which they respond to challenges, in the rates at which they change, and in their appropriateness for different situations. We usually think of hierarchies in an active sense: passing laws, setting policies, issuing orders, or establishing budgets. Higher levels do constrain lower levels in this way, but much of the time they do so in ways that are not intuitively obvious. Higher levels often constrain those further down by *not* acting, or by acting slowly (Allen and Starr 1982, Allen and Hoekstra 1992, Ahl and Allen 1996). Elites limit the behavior of subordinates by being unresponsive. While the lower levels in a social hierarchy go about the high-frequency business of daily life, the higher levels slowly issues edicts or grant appeals.

In human societies as in most living systems, information flows to higher levels and controls operate downward. Higher levels respond not to the primary forces felt by lower levels, but to information about those forces. Information flowing upward is always filtered, becoming ever more abstract and disconnected from its source, while at the same time higher levels are notoriously unresponsive to signals from below. What hierarchies do respond to is horizontal social signals—messages from or about other elites. A Russian colleague, for example, once described to me how Mikhail Gorbachev behaved in the waning days of the Soviet Union. As the union crumbled about him, and its citizens and security forces battled in the streets, the information that mattered to Gorbachev was not the needs of lower levels but his reputation in the minds of Western leaders. Along analogous lines, in August 1996 there was much discussion of establishing a high-speed rail line between Moscow and St. Petersburg. At the same time the local rails within St. Petersburg were so dilapidated that in places they ran over mud. The upper levels of civil administration in St. Petersburg responded to horizontal signals from civic elites in Moscow, while responding callously to local distress.

This may sound like hierarchy is merely a useless parasite, utterly unsuited to solving local problems. In fact

hierarchy has distinct advantages that heterarchy can never match. The advantages of hierarchy are that it can act quickly, uniformly, and over large areas. Hierarchy conveys the authority to mobilize communities to act, and to act expeditiously. Hierarchy can mobilize resources for an effective response, and can ensure that resources are distributed equitably. What hierarchy typically cannot do is to respond quickly and effectively to signals from below about new or unusual problems. Our own disaster-relief agencies, for example, have become adept at responding to flooding in the Mississippi Basin, but take excruciatingly longer to address a more unusual problem such as a catastrophic snowfall in southeastern New Mexico. National governments may unwittingly undermine traditional production systems, such as in Burgundy, because they respond to horizontal social signals, while information from below must always struggle upstream.

Heterarchy, while not so effective at mobilizing quick, large-scale responses, is better able to acknowledge and incorporate varieties of experience. Heterarchical systems work either by consensus, or by *ad hoc* consensual leadership. While the process of adjusting to new circumstances in a heterarchy is unavoidable slow, it derives legitimacy from consensus. It is based on local experience and social memory. Those who have developed a heterarchical consensus are intrinsically committed to implementing it. Yet heterarchy, like hierarchy, is by itself incomplete. While heterarchy has the advantage of incorporating diverse experiences and ensuring legitimacy of decision-making, it falters where conditions call for rapid or uniform responses, or where problems arise from outside a local context. Social memory is also far from faultless. Fekri Hassan relates a story of an advisor to the Egyptian government, who insisted that he had detected a pattern to the Nile floods of seven years of high water, seven years of low, and six years of intermediate levels. In fact the advisor had detected no such thing, and admitted privately that his model was inspired by the Koran. The inspiration is actually far older than the Koran. The advisor, probably unknowingly, perpetuated a long tradition of Egyptian social memory, which has a documented history of over four thousand years, and which is reflected in the Biblical tale of seven years of plenty followed by seven years of famine (Hassan n.d.). Local social memory, formed through heterarchies, may sometimes be a suitable guide for action, but it can also be nothing more than fable.

Scale, Context, and Landscape Change

This meandering discussion has come in a roundabout fashion to one of the fundamental dilemmas of our time: whether to confront our problems top-down, through our national government or even international conventions, or from the bottom up, based on local experiences. This dilemma, as we know, frames much of our national debate, and in various guises dominates our headlines. The dilemma becomes poignant as we realize that for the most part there are no answers or solutions that are unambiguously right or wrong. Neither hierarchy nor heterarchy is invariably appropriate or misguided. Their usefulness depends on circumstances. In a world that is interconnected at many

levels—in which the air of Albuquerque can be turned to haze by fires in southern Mexico, (such as in the third week in May, 1998), in which warming of equatorial waters increases profits for Mesilla lettuce farmers while it increases disease in the San Juan Basin—we realize that ever-closer scrutiny of our problems will likely reveal only finer and finer shades of gray. This underscores again the centrality of scaling and context, and particularly the problems that inevitably arise when there is a contradiction between the level at which problems are generated and the level at which they must be addressed.

My colleague Tim Allen is fond of saying that if fish were scientists, the last thing they would discover would be water (for example, Allen, Tainter, and Hoekstra n.d.). His point is that the most difficult matter to comprehend is the context that constrains us. It is always difficult to understand something larger than ourselves, and that is what context is (Allen and Hoekstra 1992). In a global marketplace in which the fiscal crisis in Asia may influence the level of water use in microprocessor manufacturing, and ultimately how long farmers in the Rio Grande Basin will be able to irrigate alfalfa, trying to understand our context is surely one of the most important things we can do.

The dilemma we ultimately face is that our context is increasingly distant, impersonal, unaware of us, and uncaring. In the eighteenth century the Spanish Crown probably also seemed distant, impersonal, unaware, and uncaring, but it also had little influence in the day-to-day lives of New Mexicans. Today New Mexico may be affected by decisions made on Wall Street, in Tokyo, or in the Persian Gulf, or even by the actions of angry mobs in Indonesia. The control of our local affairs is more and more in external hands.

Although the universality with which this is happening is peculiar to our era, there are precedents for it. It is worth reviewing one of these precedents briefly, for it allows us to see the long-term consequences of a locality losing control of its destiny. In the civilizations of the ancient Mediterranean, agriculture was the basis of wealth and power. The ideal landscape was one of peasant farmers producing food for the cities, sons for the armies, and taxes for the state. This was the energetic basis of the Greek city-state, and it formed a landscape in which events and processes were substantially under local control.

This began to change when Alexander the Great conquered the Near East toward the end of the fourth century B.C. The large Hellenistic kingdoms that formed in the wake of his conquests hired large armies of Greek mercenary soldiers. Suddenly Greek peasants had opportunities on an unprecedented scale to earn gold and silver serving as soldiers in Syria or Egypt, rather than farming laboriously for meager subsistence in the poor soil of Greece. The Greek countryside began increasingly to lose population from the second century B.C. When the Romans came to Greece they expropriated so much treasure that for small farmers there was a liquidity crisis. They could not earn money to pay their debts and began to lose their lands to the wealthy. The Greek landscape of peasant proprietors changed to one of ostentatious villas, owned by oligarchs who used the land less intensively—for exportable cash crops such as olive oil, wine, or livestock, and to raise prize horses and cattle. By the second century A.D. writers described the Greek countryside as unkempt and underpopulated—a sad reflection of its

former productivity. Ironically, cities flourished in this era, as oligarchs put their wealth into building public monuments. The magnificent ancient cities of the Mediterranean Basin, which we admire so much today, were partly built on the basis of rural depopulation. Greece has, in some ways, never recovered from this.

By the third century A.D. the Roman Empire was fighting for its own survival against Germanic peoples from the north and the Persians from the east. It financed its wars largely from taxes on land. It came to require that taxes be paid whether a plot of land was cultivated or not, and so tried to force underutilized lands back into production. The Greek landscape came to be repopulated, but not by a free peasantry. Farmers from the fourth century on were legally tied to their lands, or attached as tenants to great estates. These obligations were hereditary, a foretaste of the social conditions of the Middle Ages (Alcock 1993, Allen, Tainter, and Hoekstra n.d.).

The unfortunate story of the Greek landscape is one of changing context. In the era of city-states the Greek landscape developed under local control, responded to local needs, and supported the local population—much as the landscape of the Rio Grande Basin did until recently. Developments far off brought Greek independence to an end. As political units grew in size and scale, the context for the Greek landscape shifted first to the entire Near East, then to the Roman Empire and the Mediterranean Basin, then beyond the borders of the empire to the pressures exerted from central Europe and central Asia. Similarly we participate now in a Rio Grande landscape that came in the 19th century to be embedded in distant processes at national and continental scales, and in the 20th century in the international arena. We might wonder whether we have any more power to control our landscape today than the Greeks did 2,000 years ago.

Ecosystem Management: Understanding Context

As the context for the Greek landscape shifted to ever-larger arenas, in a process that extended over centuries, the Greeks lost the ability to understand what was happening to them. To lack comprehension of one's context, or the ability to influence it, makes for a depressing tale. It is also a common tale. In the first century B.C. (to give a final historical example) the Romans financed their continuous foreign and civil wars with very high production of silver coins. The metal was produced from silver-bearing lead ores, and the smelting process caused atmospheric lead pollution that circled at least the entire northern hemisphere and left a signature in the Greenland ice cap (Hong and others 1994). It is a remarkable story of context. As Marc Antony and Cleopatra dallied in the eastern Mediterranean, the silver coins they minted to pay their armies caused American Indians in the Rio Grande Basin to breathe air polluted by levels of lead not seen again until the Industrial Revolution.

The prehistoric New Mexicans of that era could not, of course, have understood this process, if they were even aware that something in their air was wrong. They could not know their context. I relate this story, and that of the Greek landscape, to show how fortunate we actually are in the

midst of all our challenges. As we have lost direct connection with our context we have also gained the ability to understand it, and that is the first step toward influencing it. We have the capacity, more than the people of any previous era, to know where we are in long-term historical processes (Tainter 1988, 1995), in the international economy, and in global environmental concerns.

We face, as I have sketched, contradictions between the levels at which problems are generated and at which they must be addressed. Many of us would no doubt prefer that local environmental problems be addressed on the basis of local experience, social memory, and heterarchy, and be resolved sustainably on the basis of local resources. Yet challenges arising from such things as atmospheric circulation patterns or international monetary flows bring us to a world of problem-solving where we depend on hierarchy, centralized solutions, and external subsidies. In such a world we will always face conflict between local and centralized problem-solving. Our approach to this conflict should start by taking advantage of the remarkable levels of knowledge that are available about our national and international context. Resolving problems locally requires equal doses of knowledge about the Basin itself and about the world at large. It is unrealistic to expect that our context will ever know us sufficiently well to avoid the sort of problem that the French government caused in Burgundy. It is our responsibility to understand our context.

As the processes at work in the world call for broader and broader realms of knowledge, most of us specialize in narrower and narrower pursuits—this or that species, or watershed, or cultural group. Accordingly we fail to see connections that ultimately we must understand, connections that form the essence of ecosystem management. How many of us would recognize that welfare reform, to take one example, is pertinent to ecosystem management? How many of us realize that for rural areas there is a fundamental contradiction between welfare reform and environmental conflict? As judicial decisions deprive rural people of their livelihoods, more and more will move to cities. Rural traditions of local knowledge, social memory, and heterarchy will decline, while the hierarchical, centralized cities will grow larger, more congested, and more polluted. Environmental protection in one area may simply shift environmental problems elsewhere.

To have the capacity to understand our context is meaningful only if we take advantage of it. We are challenged not only to develop the ability to see connections between disparate things, but more fundamentally, to change how we think so that it becomes normal and unremarkable to do so. This is the only way that the problems of the Rio Grande Basin will be understood, the best way that conflicts can be resolved, and the only way that we can discern the appropriate, ever-shifting balance among local, national, and international solutions. As the Forest Service and other agencies have developed the concept of ecosystem management in recent years, many have wondered what the term means. I suggest that it should mean precisely these matters of scale, context, and interconnection. These link the biophysical and social realms in a bond that we can dissolve artificially in specialized scientific analyses or in environmental litigation, but which can never be dissolved in actuality.

Acknowledgments

I am pleased to express my appreciation to Dr. Deborah Finch for the invitation to present this paper as a plenary address in the symposium "Rio Grande Ecosystems: Linking Land, Water, and People" (Albuquerque, 2-5 June 1998), and to Dr. T. F. H. Allen and Dr. Dale Brockway for comments on an earlier draft.

References

- Ahl, Valerie; Allen, T. F. H. 1996. *Hierarchy Theory: A Vision, Vocabulary, and Epistemology*. New York: Columbia University Press.
- Alcock, Susan E. 1993. *Graecia Capta: The Landscapes of Roman Greece*. Cambridge: Cambridge University Press.
- Allen, T. F. H.; Hoekstra, Thomas W. 1992. *Toward a Unified Ecology*. New York: Columbia University Press.
- Allen, T. F. H.; Starr, Thomas B. 1982. *Hierarchy: Perspectives for Ecological Complexity*. Chicago: University of Chicago Press.
- Allen, T. F. H.; Tainter, Joseph A.; Hoekstra, Thomas W. n.d. *Supply-Side Sustainability*. New York: Columbia University Press (in preparation).
- Bruce, James P.; Lee, Hoesung; Haites, Erik F., eds. 1996. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Cambridge: Cambridge University Press.
- Crumley, Carole L. 1979. Three locational models: an epistemological assessment of anthropology and archaeology. In: Schiffer, Michael B., ed. *Advances in Archaeological Method and Theory* 2: 141-173. New York: Academic Press.
- Crumley, Carole L. n.d. From garden to globe: linking time and space with meaning and memory. In: McIntosh, Roderick J.; Tainter, Joseph A.; McIntosh, Susan Keech, eds. *The Way the Wind Blows: Climate, History, and Human Action*. New York: Columbia University Press (in press).
- Green, S. F., G. P. C. King, V. Nitsiakos, and S. E. van der Leeuw. 1998. Landscape perception in Epirus in the late 20th century. In: S. E. van der Leeuw, ed. *The Archaeomedes Project: Understanding the Natural and Anthropogenic Causes of Land Degradation and Desertification in the Mediterranean Basin*, pp. 329-359. Luxembourg: Office for Official Publications of the European Communities.
- Hassan, Fekri. n.d. Environmental perception and human responses in history and prehistory. In: McIntosh, Roderick J.; Tainter, Joseph A.; McIntosh, Susan Keech, eds. *The Way the Wind Blows: Climate, History, and Human Action*. New York: Columbia University Press (in press).
- Hong, Sungmin; Candelone, Jean-Pierre; Patterson, Clair C.; Bouton, Claude F. 1994. Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations. *Science* 265: 1841-1843.
- Hsu, Cho-yun. n.d. Chinese attitudes toward climate. In: McIntosh, Roderick J.; Tainter, Joseph A.; McIntosh, Susan Keech, eds. *The Way the Wind Blows: Climate, History, and Human Action*. New York: Columbia University Press (in press).
- McIntosh, Roderick J.; Tainter, Joseph A.; McIntosh, Susan Keech. n.d. Climate, history, and human action. In: McIntosh, Roderick J.; Tainter, Joseph A.; McIntosh, Susan Keech, eds. *The Way the Wind Blows: Climate, History, and Human Action*. New York: Columbia University Press (in press).
- Tainter, Joseph A. 1988. *The Collapse of Complex Societies*. Cambridge: Cambridge University Press.
- Tainter, Joseph A. 1995. Sustainability of complex societies. *Futures* 27: 397-407.
- van der Leeuw, S. E.; ARCHAEOEMEDS Research Team. n.d. Land degradation as a socio-natural process. In: McIntosh, Roderick J.; Tainter, Joseph A.; McIntosh, Susan Keech, eds. *The Way the Wind Blows: Climate, History, and Human Action*. New York: Columbia University Press (in press).

Dynamic Human Landscapes of the Rio del Oso: Restoration and the Simulation of Past Ecological Conditions in The Upper Rio Grande Basin

Richard D. Periman

Abstract—The successful restoration of riparian ecosystems to sustainable conditions requires that we understand the dynamic historical relationships between humans and the environment. Research is needed that measures the continuing effects of past human activities on contemporary ecosystem structure and function. An interdisciplinary approach is needed that incorporates expertise from archaeology, paleoecology, plant ecology, and geology. In this paper, I discuss how prehistoric peoples have altered ecological processes and changed the vegetation and overall physiography of northern New Mexico's Rio del Oso Valley. In the Rio del Oso study, we are using paleobotanical, sedimentary, archaeological, and historical data sets to reconstruct past vegetational structure and function, and to identify the cumulative influences of past human activities on today's ecosystems. This information is used to generate three dimensional simulations of environmental conditions through time. These computer reconstructions and analyses of past landscapes will give land managers a greater range of information for use in planning, decision making, and restoration.

Historical Information and Restoration

The landscapes of the Rio Grande and its tributaries have been modified, shaped, and domesticated by humans for at least twelve millennia. Yet the myth of the pristine wilderness prevails among those intent on restoring or preserving this land in its so-called "pre-settlement conditions" (cf. Grumbine 1992). Often, "pre-settlement" refers to pre-A.D. 1850, seemingly negating thousands of years of Native American land use and environmental influence (Quigly and others 1996). Not only does this lack of ecological understanding limit our knowledge of past ecosystem dynamics, it also restricts the future range of restoration efforts possible in the Basin.

The National Resource Council defines restoration as the return of an ecosystem to a close approximation of its conditions before disturbance (1992). Before the objectives of

a restoration effort can be established, the ecosystem needs first to be evaluated. Appropriate reference conditions need to be established as goals for restoration of various ecosystem components. The interactions between biotic and abiotic components of the ecosystem must be identified. Additionally, the significant linkages between biotic communities for reestablishing historic ecosystem structure must be understood. Christensen and others emphasize that ecosystem management needs clear long-term operational goals and sound ecological models. Understanding ecological complexity and interconnectedness, recognizing the dynamic character of ecosystems, and acknowledging humans as ecosystem components is crucial for successful restoration, as well as sustainability (Christensen and others 1996:669-670).

Evaluation of an ecosystem's historic structure and function for the purposes of restoration, as indicated above, needs to include study of long-term anthropogenic processes. However, our understanding of how landscapes have developed under cumulative human influences remains limited, and assumptions, rather than the systematic study of past conditions, perpetuate myths about ecosystem development. For example, degradation by over-grazing and other extractive processes may appear obvious. However, we often know little about how a specific ecosystem may have been manipulated, altered, and maintained by humans before such degradation took place. What were the dynamic historical conditions of landscapes we now consider degraded? What long-term processes, including human processes, contributed to this pre-grazing environment? Although historical documentation from personal journals and photographs seem to answer these questions, such sources provide only a glimpse of past landscapes from a synchronic visual, spatial, and temporal perspective. For restoration to be successful, a more comprehensive and diachronic knowledge of past ecosystem dynamics that includes anthropogenic processes needs to be developed.

Addressing this lack of information, Rocky Mountain Research Station's Cultural Heritage Research Work Unit is developing an interdisciplinary approach for quantifying anthropogenic influences on ecosystem structure and function. Our first study area is located in northern New Mexico's Rio del Oso Valley where a variety of cultures have shaped and changed the landscape for at least 7,000 years. In this paper, I first provide a short discussion of how human-induced environmental change has been identified in various areas world-wide. Then I describe the Rio del Oso study and our use of paleoenvironmental information to construct visual models of past vegetational landscapes. Finally I offer a refinement to our conception of restoration.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Identifying Past Anthropogenic Ecological Change

Human-induced environmental change has been identified in environments around the globe. In a review of pollen and charcoal studies from around the world, Walker and Singh discuss a broad range of data from Western Europe, Africa, Asia, Australia, and North and South America. They suggest that the event most detectable in the pollen and microcharcoal record is deforestation, and that this was caused and aided by human-set fires (1993:108). Additionally, increases in microscopic charcoal, changes in fossil pollen assemblages, and faunal extinctions also indicate human occupation (Burney 1993 and 1997; Chambers 1993a). Paleobotanical research in the Peruvian Andes shows that human-caused deforestation for agricultural purposes took place at least 4,000 years ago (Chepstow-Lusty and others 1998). Throughout the British Isles as early as 10,000 B.P. (before present) reduced arboreal pollen, with a corresponding increase in microscopic charcoal and archaeological evidence, indicates that human activity was responsible for the transformation of forest into peatlands (Caseldine and Hatton 1993; Edwards 1988; Simmons 1988). On the island of New Guinea forest clearing is suggested by changes in pollen assemblages and significant increases in microscopic charcoal dating before 30,000 B.P. The human role in this environmental change is corroborated by the presence of stone axes and adzes (possibly used for forest clearing), from archaeological sites that date to the same period. Indeed, such clearing of vegetation may have begun much earlier in New Guinea, as suggested by the discovery of ground-stone axes, complete with grooves for hafting to a handle, dating to at least 40,000 B.P. (Hope and Golson 1995:821-823).

In the Americas, ethnographical accounts, historical records, and archaeological information show that people directly affected ecosystems by manipulating vegetation.

Landscape patterns in native California were altered by human activities such as sowing and broadcasting seeds, transplanting shrubs and small trees, and pruning a variety of plants to induce greater productivity (Blackburn and Anderson 1993:19). Fire was used to clear vegetation and increase the productivity of plants and animals important for human survival. By 1492 agricultural fields were common, as were settlements with networks of roads and trails, all of which had local impacts on soil, microclimate, hydrology, and wildlife (1992:370). Subsequently, the introduction of Old World livestock, intensive agriculture, and industrial development into existing Native American land-use systems resulted in a combination of anthropogenic influences producing hybrid landscapes (Whitmore and Turner 1990:416).

Human actions of one century have a cumulative environmental effect when combined with human actions from another century. Succeeding occupation and abandonment causes a landscape's developmental trajectory to evolve in a new direction (see Tainter and Tainter 1995:28). Over the course of generations, repeated and changing levels of human disturbance become part of the ecological processes in an ecosystem (Allen and Hoekstra 1992:272). Each new anthropogenic landscape is built upon an antecedent landscape. Such is the case in the Rio Grande Basin of New Mexico where Puebloan agricultural landscapes were constructed upon those created by earlier foragers, and Spanish colonial landscapes were built upon Puebloan farming landscapes.

Rio Del Oso Study

The Rio del Oso is an eastern-flowing tributary of the Rio Chama that drains the northern portion of the Jemez Mountains of north central New Mexico (fig. 1). Most of the Rio del Oso watershed is administered by the Santa Fe

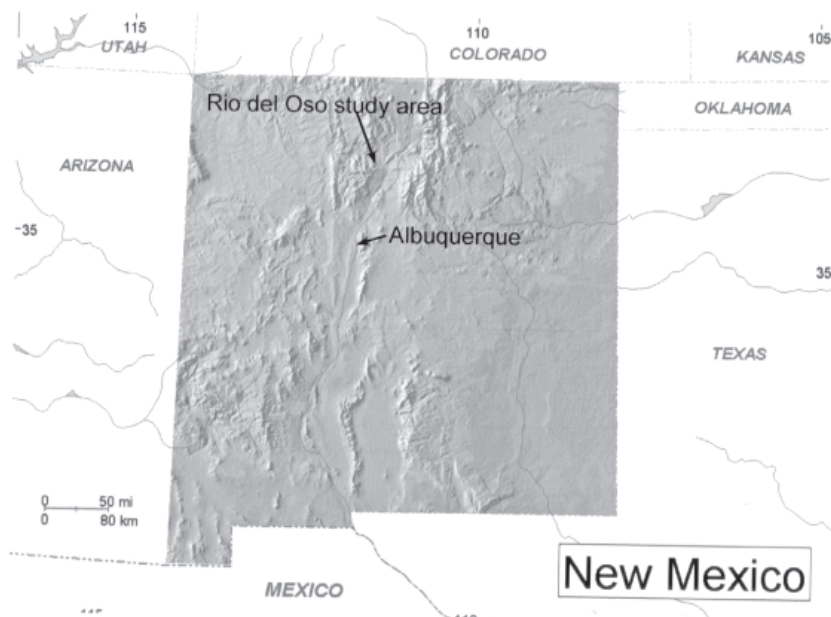


Figure 1—Rio del Oso study location.

National Forest. I selected the Rio del Oso as my study area because of its complex richness of recorded archaeological sites. More than 280 archaeological sites including four large pueblos have been recorded in the lower portion of the drainage (Anschuetz 1995). Although the anthropogenic qualities of the Rio del Oso landscape may not be readily discernable, this place has been shaped into the landscape we see today by thousands of years of human activity. The archaeological data of the Rio del Oso valley covers the Archaic period (5500 B.C. to A.D. 600), the Coalition period (1200-1325), the Classic period (1325-1600), and the historic Hispanic period (beginning c.1600).

During the Archaic period hunter-gatherers occupied the valley and likely affected the Rio del Oso landscape by burning its vegetation, dispersing seeds, and selectively harvesting plant and animal species. So far, archaeologists have found little evidence for human occupation of the valley between the late Archaic and the Coalition periods. However, from A.D. 1200 through 1600, the Puebloan groups greatly altered the valley by creating villages, agricultural features and other systems of land and water use (Anschuetz 1995).

When historic Hispanic groups moved into the Rio del Oso they constructed small settlements and farms, built roads and water ditches, and produced their own unique landscape patterns in the valley (Wozniak and others 1992). During the first part of this century the Forest Service assumed administration of the area, creating yet another pattern of human-use and environmental change by restricting grazing, building roads and fences, and attempting to restore vegetation.

Data Sources and Methods

The primary goal of our research is to develop an integrated, interdisciplinary approach to identify and measure cumulative anthropogenic effects on landscapes. Data in the Rio del Oso project ranges from historical and ethnographic records to archaeological and paleobotanical data. The Santa Fe National Forest has provided digital vegetation data, land type, watershed coverages, and Digital Elevation Models (DEMs), and has made all archaeological site records and field maps available. Additionally, I am using Forest Service administrative records, 1935 aerial photos, and 1991 color infrared aerial photos to reconstruct the valley's environmental history and document vegetational change for this century.

With these data map layers have been developed including vegetation, landform, watershed, and archaeological site coverages. All four data sets will be used, either individually or in combination, to develop visual models of the existing vegetational environment. In this interdisciplinary study, we are using archaeological, paleobotanical, sedimentary, geomorphological, and historical data to identify past human-induced ecological change through time. Our research questions include:

1. What interdisciplinary data sources, research methods, and analytical approaches can be used to develop GIS data layers of past and cumulative human-created landscapes?

2. Using the above methods, can we identify and quantify the extent of human-induced vegetational change for specific periods relative to the different technologies and economies of the cultures that occupied the land during those times?
3. Using data from the above sources, is it possible to produce three-dimensional landscape models that accurately illustrate the environmental history of an area? Which sources of information are the most useful? Do the resulting landscape simulations provide a useful model for understanding human and environmental interactions?
4. Is it possible to develop a set of methods and techniques that can be applied to ecosystems different from those in northern New Mexico?

Fieldwork and Paleobotanical Analysis

Fieldwork began during the summer of 1996 with the collection of soil samples from an exposed, 5 m stratified section of alluvial sediments. Pollen, phytoliths, microscopic charcoal, and radiocarbon samples were extracted from each stratum. Four prehistoric human hearths, or ash-stain features, were uncovered while preparing the vertical surface of the cutbank for sample collection. During sampling, geologist Dr. Stephen A. Hall (geologist and research partner, Department of Geography, University of Texas at Austin) identified seven distinct paleosols in the profile (Hall personal communication 1996).

In 1997 pollen, phytoliths, and microscopic charcoal were extracted from the samples by paleobotanist Dr. Linda Scott Cummings (paleobotanist and project collaborator, Paleo Research Inc., Denver, CO). Radiocarbon dates were produced, ranging from 3515 B.C. to A.D. 1350, for the 24 strata. The pollen analysis, when matched with the radiocarbon dates, suggests fluctuations in vegetation and microcharcoal levels over the past 5,512 years. During her analysis Dr. Scott Cummings identified corn pollen in three of the levels dating between 1360 and 1225 B.C., associated with hearths. Although presently inconclusive, this may be some of the oldest evidence of corn in the Rio Grande Basin (see Minnis 1992).

Additionally, surface samples for pollen, phytoliths, and microscopic charcoal were collected from areas near our stratified section. The data from those samples are being used to develop control ratios of pollen frequencies to trees and shrubs-per-acre. These ratios will be used with the three-dimensional GIS to reconstruct the hypothetical tree and shrub densities of past landscapes.

During reconnaissance of the valley in 1997, other stratified deposits containing buried soils were identified, and sediment samples were taken from newly discovered cutbanks as well as from a peat bog located at the head of the drainage. New surface samples were also collected from the Rio del Oso's riparian habitat. We conducted additional analysis and developed new methods for analyzing opal phytoliths during 1998. Dr. Scott Cummings identified an abundance of phytoliths that appear to be from woody plants, possibly from tree species. Appropriate phytolith comparative collections being unavailable in the United States, she took the phytolith samples to Israel where they

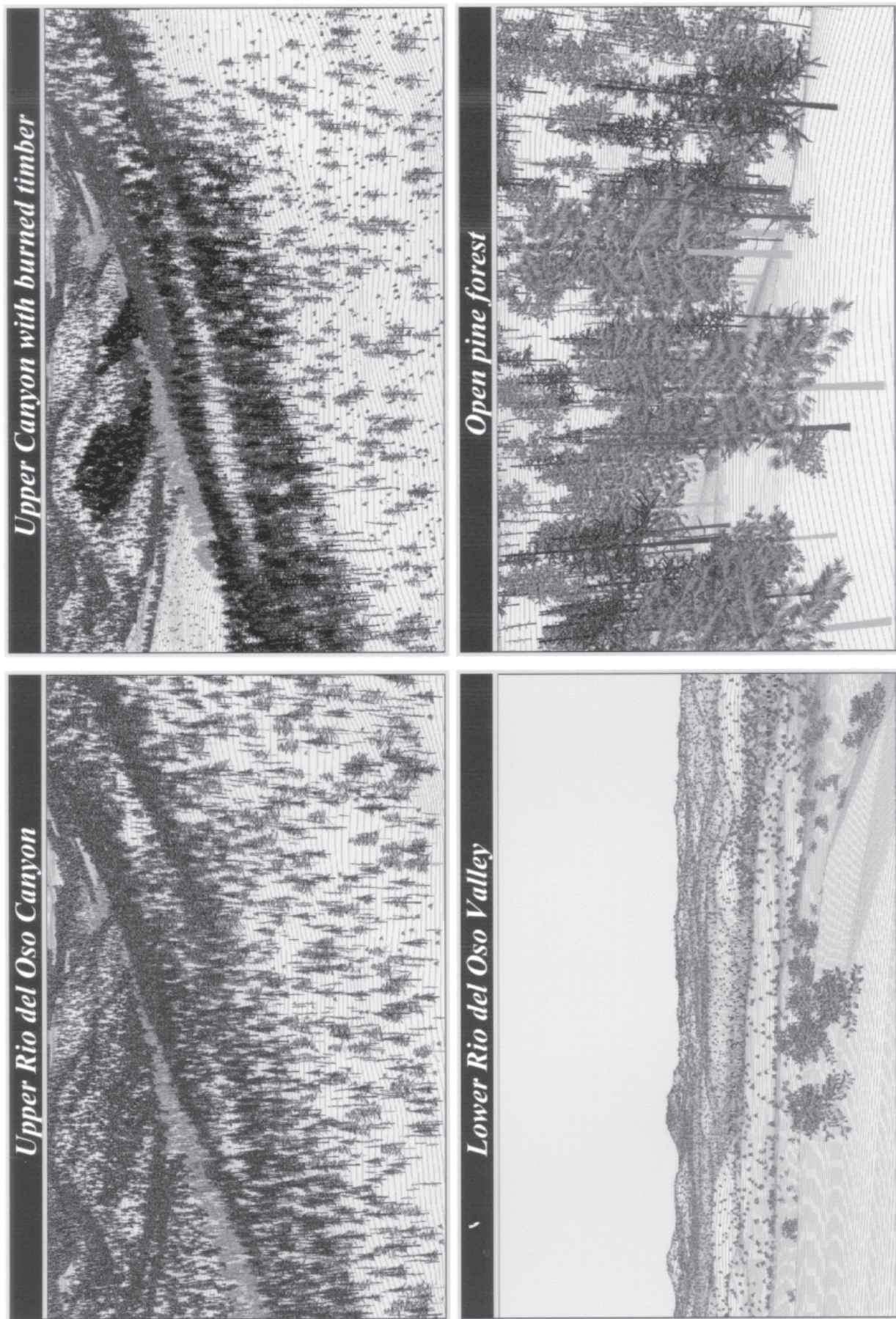


Figure 2—Hypothetical simulations of Rio del Oso landscapes.

were compared to tree phytoliths identified by Israeli scientists (Scott Cummings personal communication 1998).

In 1999 we will excavate backhoe trenches at the first sample location and at three of the localities identified in 1997. Additional samples will be taken from those locations and the trenches will enable further study of the geomorphology of the Rio del Oso Valley. Future research will include the calculation of areas affected by prehistoric activities, the identification of zones around archaeological sites and features representing levels of land use, and the refinement of interdisciplinary methods for application to other types of landscapes. We also will continue to establish indices of surface pollen, phytolith, and microscopic charcoal, which represent different habitat types in the Rio del Oso drainage.

Simulation of Past Landscapes

The Rio del Oso landscape simulations are based on vegetational assemblages reconstructed from paleobotanical, ecological, archaeological, and historical data. Analyses, of the paleobotanical samples by Dr. Scott Cummings will identify variations in absolute and relative pollen and phytolith frequencies, assemblages representing specific habitats, past fire frequencies, and human-induced vegetational change through time. The quantities of vegetation (for example, trees-per-acre) will be derived from the surface and subsurface data as described above. This information will be used to produce three-dimensional simulations of past vegetational landscapes (fig. 2) from a variety of viewsheds within the Rio del Oso drainage for each stratigraphic level. The simulations are grouped according to their radiocarbon dates into corresponding archaeological periods.

The simulations are created using a visual simulation system designed by Resource Analysis Systems for natural resource management. This software, called Visual F/X, produces three-dimensional landscape perspective scenes as if seen through a 35mm camera with a 50mm lens. It allows the user to define up to 14 basic tree forms and control the crown width, height, and trunk diameter. A DEM (digital elevation model) is used as the base map and vegetation density is derived from estimated trees- and shrubs-per-acre figures. Additionally, we utilize digital vegetation, soil, timber, and watershed map data. The paleobotanical data (for example, pollen) are grouped by ecological or phytogeographic categories to help illustrate how plant distribution and ecological conditions have changed through time (Pearsall 1989:286). These data will be used to help identify temporal and spatial fluctuation of vegetation type areas, for example, riparian cottonwood-willow habitat.

Linking Past Vegetational Patterns to Ecological Processes

Along with compiling paleobotanical data that show ecological change, and represent that change graphically, we also need to identify reliable indicators of past human-caused environmental change (see Birks and others 1988).

How does analysis of pollen and other organic particles indicate human manipulation and change of the environment? The answer to this question may depend on the "sensitivity of an ecosystem to human exploitation and the degree to which this is reflected in the pollen analytical signal" (Walker and Singh 1993:104). In order to discern "natural" paleobotanical change from that caused by human manipulation, Walker and Singh suggest four criteria:

1. It [the paleobotanical record] should reflect ecological processes operating at levels and rates that are unprecedented under 'natural' conditions but are readily explicable as resulting from human actions of defined kinds.
2. The necessary human activities should be within the technological capacity of prehistoric peoples of the relevant age and region.
3. There should be some acceptable reason why the humans might have taken the hypothesized action (ideally exemplified by the pollen itself, for example, crop pollen).
4. There should be strong evidence (ideally artifacts stratified into the pollen-analyzed deposits) for human occupation at the appropriate time within the pollen catchment (Walker and Singh 1993:104-105).

When these criteria are applied to the pollen and charcoal records of Europe, there is striking evidence for an anthropogenic influence resulting in the transformation of western European forests between 7000 and 6000 B.P. This ecological change is attributed to clearing land for agriculture (Walker and Singh 1993:106-107). Although the Rio del Oso project includes the study of landscapes created before and after the introduction and use of agriculture, these criteria will be used to help determine human-induced environmental change from that caused by climate change and other natural occurrences. However, I have added another criterion to help with the identification of anthropogenic change: Two or more paleobotanical indicators, for example, pollen, phytoliths, macrobotanical remains, packrat middens, ethnographic information, or historical photographs should correlate when data sets are analyzed and compared.

An essential part of this analysis involves bridging the gap between the paleobotanical record and interpretation of vegetational landscapes. This interpretation is very important for producing the simulations discussed above. Pollen and phytolith analysis identifies pollen producing plants inside and outside an ecosystem. The paleobotanical record accounts for a generalized sample of vegetation from a large area (Pearsall 1989).

Designating a group of species that *represents* a specific vegetation community will help describe the vegetational variation of specific habitats within the Rio del Oso landscape. For example, an assemblage of species may represent riparian areas while another group may represent species growing mainly in upland habitats. It should be possible to estimate vegetation density by comparing representative species groups to the index surface of samples and then compare the variation in pollen frequencies for each species and each habitat assemblage. Such densities would be calculated as trees and shrubs per acre for spatially discrete habitats. From this record a specific group of plant species may be identified within a given range of pollen frequencies

which would identify human alteration of vegetational patterns. Comparing the fossil habitat assemblages and their associated species frequencies to an index of current habitat pollen frequencies gives us an estimate of the expansion and contraction of individual habitats through time (Berglund and others 1996; Pearsall 1989).

However, vegetational reconstructions are only the first step in understanding how the Rio del Oso landscape developed under human influence. As stated earlier, we also need to understand ecological processes. The following definitions for *ecosystems*, *ecological landscapes*, *anthropogenic landscapes* can be used to link landscapes, ecosystems, and human influences. Using Lindeman's definition, an ecosystem is "the system composed of physical-chemical-biological processes active within a space-time unit of any magnitude, i.e., the biotic community plus its abiotic environment" (1942:400). An ecological landscape is the spatial matrix in which organisms, populations, and ecosystems are set (Allen and Hoekstra 1992:56). Anthropogenic landscapes are formed within and become integral to ecological spatial matrices; they include process as well as form. Such landscapes are "land shapes," areas which are made up of a distinct association of forms both physical and cultural (Sauer 1925:25-26). Landscape is the way we produce or

reconstruct our physical, material world; a kind of human sculpting of the natural universe (Wilson 1992).

In figure 3, ecosystem processes occurring through time (a) are represented as cyclical, components, while the three surfaces represent the landscape spatial matrix (b). Change in landscape vegetation and geomorphology occurs within the spatial matrix and is represented on the landscape surfaces as differing vegetation (c). Human activities like burning vegetation or practicing agriculture affect ecosystem processes. Over time these human-induced processes, or changes in processes, affect plant community composition, habitat size, as well as carbon, nutrient, water, and decomposition cycles. Changes in function (ecosystem processes) and structure (vegetation patterns and geomorphology) result in variations in the placement of landscape components (see Hobbs 1997). Changes in technologies result in changes in ecological processes. As new, human land-use practices change vegetational patterns (for example, the introduction of agriculture), new anthropogenic landscapes are created within and are part of the ecosystem and spatial matrix. Over thousands of years, this complex relationship between humans and the environment has had a cumulative effect on landscape development.

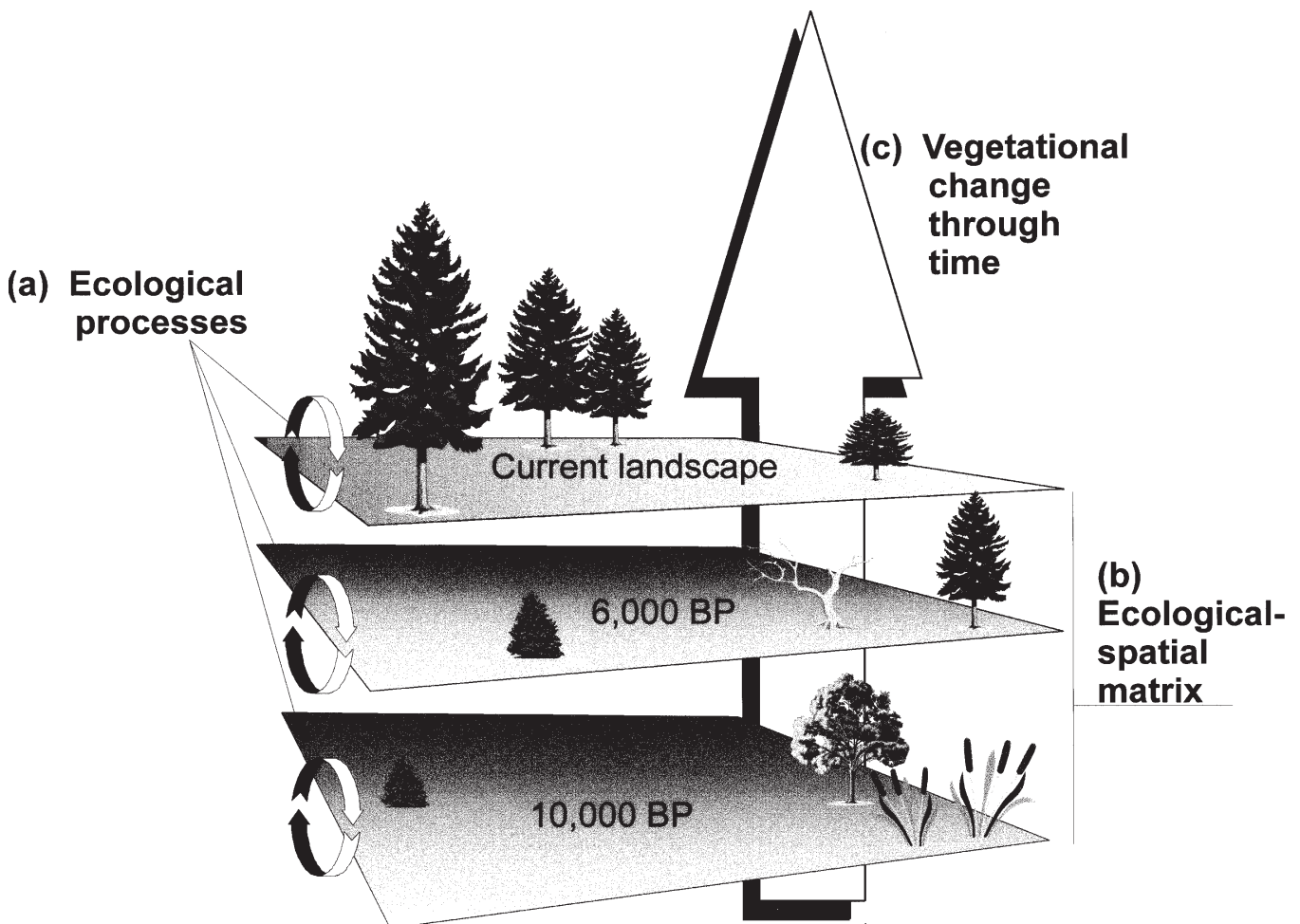


Figure 3—Model of long-term human influences in landscape development. Humans affect landscapes at all levels (a, b, and c).

Restoration

In places like the Rio del Oso Valley human influence is inextricable from the other components and processes that created the landscape we see today. The relationships among ecological and cultural processes can be important for restoration. An alternative to merely restoring vegetative structure (replanting etc.) using reference conditions would be to identify a set of multidimensional *reference dynamics* (natural and anthropogenic). These reference dynamics should include an understanding of the: (1) paleoecological evidence of natural and human-induced change including change in biodiversity and abundance of specific species; (2) technologies and processes responsible for specific environmental change; and (3) temporal and spatial intensity and extent of such change to the ecological-spatial matrix. By understanding these components, a land management agency has more options for restoring and sustaining an ecosystem within a range of ecological, climatic, and sociological constraints.

Conclusions

Public demand for the restoration of ecosystems degraded by grazing, logging, and other extractive uses, daily challenges the ingenuity and resourcefulness of land management agencies. The landscapes we manage today have been modified, shaped, and domesticated by humans for at least twelve millennia. The concept of ecological restoration involves human intervention in ecological processes. Indeed, the word "degradation" reflects human values and varies among cultures (see van der Leeuw 1998). Just as past cultures played an integral role in creating the landscapes we see today, restoration involves the manipulation of ecological processes to achieve landscape conditions desired by society. Current conflicts over public land management is to some degree based on differing definitions of degradation and what ecological conditions are considered desirable (see Raish this volume).

Models of past landscapes like those being produced for the Rio del Oso can help managers to understand better the dynamic processes required for restoring ecosystems to desired conditions. Creating landscape simulations based on paleobotanical, archaeological, and geological data will enable decision-makers to view their restoration options within a *range* of dynamic processes leading to sustainable conditions.

Acknowledgments

I thank Joe Tainter whose support and guidance have been inestimable. I wish to thank Liz Kaplan, Karin Periman, Nora Altamirano, and Madelyn Dillon for their editorial suggestions. I extend my sincere gratitude to Brian Kent and Deborah Finch for supporting this research. From this study's beginning they have recognized the importance of understanding that humans have been integral to the development of Rio Grande Basin landscapes for thousands of years.

References

- Allen, T.F.H.; Hoekstra, T.W. 1992. Toward a unified ecology. New York: Columbia University Press. 384 p.
- Anschuetz, K.F. 1995. Preliminary report for the 1993 field season, the University of Michigan Rio del Oso archaeological survey, Española Ranger District, Santa Fe National Forest. Santa Fe, NM: U.S. Department of Agriculture, Forest Service, Santa Fe National Forest Supervisor's Office. 123 p.
- Burglund, B.E.; Birks, H.J.B.; Ralska-Jasiewiczowa, M.; Wright, H.E. eds. 1996. Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. Chichester, UK: John Wiley & Sons. 764 p.
- Blackburn, T.C.; Anderson, K. 1993. Introduction: Managing the domesticated environment. In: Blackburn, T.C.; Anderson, K. eds. Before the wilderness: environmental management by native Californians. Menlo Park, CA: Bellena Press. 15-25.
- Burney, D.A. 1993. Recent animal extinctions: recipes for disaster. *American Scientist*. 81(6): 530-541.
- Burney, D.A. 1997. Tropical islands as paleoecological laboratories: gauging the consequences of human arrival. *Human Ecology*. 25(3): 437-457.
- Caseldine, C.; Hatton, J. 1993. The development of high moorland on Dartmoor: fire and the influence of Mesolithic activity on vegetation change. In: Chambers, F.M. ed. Climate change and human impact on the landscape: studies in palaeoecology and environmental archaeology. London: Chapman & Hall. 119-131.
- Chambers, F.M. 1993a. Climate change and human impact on the landscape: studies in palaeoecology and environmental archaeology. London: Chapman & Hall. 303 p.
- Chambers, F.M. 1993b. Part four, climate change and human impact: relationships and interaction: introduction. In: Chambers, F.M. ed. Climate change and human impact on the landscape: studies in paleoecology and environmental archaeology. London: Chapman & Hall. 203.
- Chepstow-Lusty, A. J.; Bennett, K.D.; Fjeldsa, J.; Kendall, A.; Galiano, W.; Herrera, A.T. 1998. Tracing 4,000 years of environmental history in the Cuzco area, Peru, from the pollen record. *Mountain Research and Development*. 18(2): 159-172.
- Christensen, N.L.; Bartuska, A.M.; Brown, J.H.; Carpenter, S.; D'Antonio, C.; Francis, R.; Franklin, J.F.; MacMahon, J.A.; Noss, R.F.; Parsons, D.J.; Peterson, C.H.; Turner, M.G.; Woodmansee, R.G. 1996. The report of the Ecological Society of America Committee on the scientific basis for ecosystem management. *Ecological Applications*. 6(3): 665-691.
- Dahm, C.N.; Cummins, K.W.; Valett, H.M.; Coleman, R.L. 1995. An ecosystem view of the restoration of the Kissimmee River. *Restoration Ecology*. 3(3): 225-238.
- Deneven, W.M. 1992. The pristine myth: the landscape of the Americas in 1492. *Annals of the Association of American Geographers*. 82(3): 369-385.
- Edwards, K.J. 1988. The hunter-gatherer/agriculture transition and the pollen record in the British Isles. In: Birks, H.H.; Birks, H.J.B.; Kaland, P.E.; Moe, D. eds. The cultural landscape - past, present and future. Cambridge, UK: Cambridge University Press. 255-266.
- Grumbine, R.E. 1992. Ghost bears: exploring the biodiversity crisis. Washington, DC: Island Press. 294 p.
- Hobbs, R. 1997. Future landscapes and the future of landscape ecology. *Landscape and Urban Planning*. 37: 1-9.
- Hope, G.; Golson, J. 1995. Late Quaternary change in the mountains of New Guinea. *Antiquity*. 69: 818-830.
- Lindeman, R.L. 1942. The trophic-dynamic aspect of ecology. *Ecology*. 23(4): 399-418.
- Minnis, P.E. 1992. Earliest plant cultivation in the desert borderlands of North America. In: Cowan, W.; Watson, P.J. eds. The origins of agriculture: an international perspective. Washington DC: Smithsonian Institution Press. 121-141.
- National Research Council. 1992. Restoration of aquatic ecosystems: science, technology, and public policy. Washington DC: National Academy Press.
- Pearsall, D.M. 1989. Paleoethnobotany: a handbook of procedures. San Diego, CA: Academic Press. 470 p.

- Quigley, Thomas M.; Haynes, R.W.; Graham, R.T., eds. 1996. Integrated scientific assessment for ecosystem management in the interior Columbia Basin and portions of the Klamath and Great Basins. General Technical Report PNW-GTR-382. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. 303 p.
- Sauer, C.O. 1925. The morphology of landscape. University of California Publications in Landscape. 2(2): 19-53.
- Simmons, I.G. 1988. Vegetation change during the Mesolithic in the British Isles: some amplifications. In: Chambers, F.M. ed. Climate change and human impact on the landscape: studies in palaeoecology and environmental archaeology. London, UK: Chapman & Hall. 109-118.
- Tainter, J.A.; Tainter, B.B. 1996. Riverine settlement in the evolution of prehistoric land-use systems in the Middle Rio Grande Valley, New Mexico. In: Shaw, D.W.; Finch, D.M. eds. Desired future conditions for southwestern riparian ecosystems: bringing interests and concerns together. 1995 Sept. 18-20, 1995; Albuquerque, NM. General Technical Report RM-GTR-272. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 22-32.
- van der Leeuw, S.E. 1998. Introduction. In: van der Leeuw, S.E. ed. The Archaeomedes project: understanding the natural and anthropogenic causes of land degradation and desertification in the Mediterranean Basin. Luxembourg: Office of Official Publications of the European Communities. 438 p.
- Walker, D.; Singh, G. 1993. Earliest Palynological records of human impact on the world's vegetation. In: Chambers, F.E. ed. Climatic change and human impact on the landscape: studies in paleoecology and environmental archaeology. London, UK: Chapman & Hall. 101-108.
- Whitmore, T.M.; Turner, B.L.I. 1990. Landscapes of cultivation in Mesoamerica on the eve of the conquest. *Annals of the Association of American Geographers*. 82(2): 402-425.
- Wilson, A. 1992. The culture of nature: North American landscape from Disney to the Exxon Valdez. Cambridge, MA: Blackwell Publishers. 368 p.
- Wilson, J.B.; King, W.M. 1995. Human-mediated vegetation switches as processes in landscape ecology. *Landscape Ecology*. 10(4): 191-196.
- Wozniak, F.J.; Kemrer, M.F.; Carillo, C.M. 1992. History and ethnohistory along the Rio Chama. Albuquerque, NM. U.S. Army Corps of Engineers, Albuquerque District.

Water Democracies on the Upper Rio Grande, 1598-1998

José A. Rivera

Abstract—The acequia irrigation systems of northcentral New Mexico and southern Colorado are the oldest, continuously functioning water management institutions in the United States. For a period of four hundred years, 1598-1998, the acequias have sustained the agropastoral economies of the region while protecting the watershed resources on which downstream water stakeholders depend. The acequia customs of sharing and system of self-government provide a framework for sustainable resource use into the twenty-first century in a time of changing and often conflictive values. Continuance of these traditional institutions, however, depends on how successfully they adapt to the new realities of the emerging water markets in the region.

This year marks the *cuarto centenario* or 400th anniversary of the establishment of the first Spanish colony in *El Reino del Nuevo México*, the northern border province of *Nueva España* in the New World. On July 11, 1598, *Capitán General* Juan de Oñate arrived at present day San Juan Pueblo and established the first European colony in this northern Spanish frontier, calling it *San Juan de los Caballeros* (Simmons 1991). During the early period of Spanish exploration and expansion, *Nuevo México* loosely encompassed the territory north of *Nueva Viscaya* (Chihuahua) with no fixed boundaries west or east (D. Cutter and Engstrand 1996). From the start, Oñate and his party conducted expeditions in both directions; but they expended the majority of their efforts at establishing a permanent colony and seat of government, initially at San Juan on the eastern banks of the *Río del Norte*, as the Río Grande was known at the time. Here, according to Oñate biographer Marc Simmons (1991), Oñate planned to build a new municipality he intended to call *San Francisco de los Españoles*. With the help of 1500 laborers from the nearby Indian Pueblos, construction of a ditch was begun to support this new town site and eventual capital city of *El Reino del Nuevo México* (Simmons 1991; Hammond and Rey 1953).

For unknown reasons, Oñate abandoned his plans for the building of a Spanish municipality in the vicinity of San Juan, and instead he moved the colony to the west bank of the *Río del Norte* directly across from the original site (Simmons 1991). This settlement was called San Gabriel,

itself built on a partially abandoned Tewa Pueblo. Here, too, one of the first tasks of the Oñate party was to construct an irrigation ditch sufficient to support the expansion of cultivated fields essential for the permanent occupation of the Spanish colony (Baxter 1997). San Gabriel (now known as Chamita) remained as the capital of the fledgling province throughout Oñate's term as governor. In 1610 a subsequent governor, Pedro de Peralta, moved the capital to a more strategic location at Santa Fe, where once again, the construction of a municipal irrigation system was a primary and early public works project. Two *acequia madres* (main canals) were dug to irrigate fields on both sides of the *Río de Santa Fe*, the river that passed through the center of the new and permanent capital city (Simmons 1972; Twitchell 1925).

The occasion of the *cuarto centenario* anniversary provides an opportunity to recognize the cultural, historic, political, economic and ecological importance of the acequia-based irrigation systems constructed at San Gabriel, Santa Fe, and other later sites. Following Spanish laws, the acequia appropriators long ago evolved customary rules for the administration and equitable distribution of water resources, traditions that have continued in force but that differ in some respects with modern legal systems in the western states. Though acequias are built systems carved into the natural landscape, these earthen ditches in a sense mimic the physics of the natural watercourses in the surrounding area as much as alter them, relying as they do on the relatively benign technology of gravity flow. Acequias contribute to the diversity of the landscape by extending the biotic environment beyond the narrow confines of the river channels from where they take water for the purposes of irrigation.

In the semiarid environment of the uplands region, the external effects of these ditches are largely beneficial, a characteristic of acequia watercourses that needs to be more widely recognized by other water stakeholders and the general public. In most uplands river valleys, the acequia communities are the first points of diversion of headwaters streams. Their location in the area of origin upstream makes them central to the maintenance of pure and clean stream waters for all categories of uses downstream. Sustainability of these communities, thus, coincides with values that acequia irrigators hold in common with the multitude of other users throughout the watershed: healthy forest ecosystems and benign upstream uses preserve water quality for everyone. In this sense, the historic stewardship role of acequia communities should be recognized, validated and supported in modern water planning, state policies and laws.

Acequia agriculture also should be credited for providing the social organization critical to the goals of Spanish colonization in the high altitude region which at the time formed the northern borders of the vast Spanish empire in the New World. This accomplishment makes the acequias of present

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Some sections of this paper appeared in a recent book by the author, "ACEQUIA CULTURE: Water, Land, & Community in the Southwest," University of New Mexico Press, Fall 1998.

day northcentral New Mexico and southern Colorado the oldest, continuously functioning water management institutions in the United States. For centuries the irrigators have operated their acequias as water democracies, governing their own water affairs, electing their officers, and enforcing their own rules. Functioning as they have under three sovereigns (Spain, Mexico, and the United States), these local acequia institutions have thus far survived the test of time with only minor adjustments in their customary practices, traditions and system of self-government.

Also, we should recognize that the first water laws of New Mexico were based on customary usage and local traditions passed on from generation to generation. These acequia practices were crystallized into law by the New Mexico territorial assemblies of 1851 and 1852. In southern Colorado, the San Luis People's Ditch holds the oldest water rights in the entire state, a distinction commemorated by way of a state monument which marks the location of this "oldest continuously used ditch in Colorado, with court decree priority right no. 1." For centuries the acequias in both states have carried on a tradition of resource stewardship and can be credited with adopting the first environmental laws to protect water quality and to promote water conservation and public health. The remaining sections of this paper demonstrate these and many other contributions of the acequia waterworks located on the valley bottomlands of the Río Grande watershed and other river systems in the region. The paper concludes with a discussion of a few contemporary issues impacting the acequia communities in a time of changing realities and the emerging water markets that challenge the continuance of the historic acequia institution into the 21st century.

Evolution of Watershed Communities

Since the establishment of the first Spanish colony at *San Juan de los Caballeros*, the upper Río Grande has served as a continuous homeland for *hispano mexicanos*, a mixed race of people who migrated as colonists from central Mexico in order to occupy and settle the northern borders of New Spain. Watersheds have long defined the boundaries of community in this semiarid environment, not only as hydrologic units that support local agropastoral economies, but also as the basis for social and political organization (Rivera and Peña, 1998). Nestled within the canyons and valley floors, tiny rural villages dot the spectacular and enchanting landscape. These settlements survive due to the infrastructure of earthen ditches, native engineering works known locally as acequias, that divert the precious waters from the river systems to extend life into every tract and pocket of arable bottomland. (Rivera 1996; Carlson 1990). In the uplands physiography of northcentral New Mexico and southern Colorado, these watercourses of rivers, streams, creeks and acequias are the single most critical resource needed for the survival of all forms of life: biotic, animal and human.

The acequia-based farming methods that are still utilized extensively in the upper Río Grande have Roman, Moorish-Iberian as well as indigenous, Pueblo Indian roots. The Spanish and Mexican settlers who occupied the river corridors

of the northern frontier melded the Roman and Moorish-Iberian customs transplanted from Spain to Mexico with the irrigation practices they observed at many Pueblo Indian villages during their expeditions of the late sixteenth century (Simmons 1972). As to their own contributions, these *pobladores* adapted and expanded irrigation farming throughout the region, including diversions built on the mightiest stretches of the Río Grande, the Río Chama, the Río Pecos, the Mora and Gallinas rivers, and others. Constructed of locally available materials, the acequia irrigation works included an earthen presa (dam), the acequia madre (main canal), and a network of *sangrías* or lateral ditches that irrigated the individual parcels of farmland. Together, the system of rivers, streams and acequias dominated the natural and rural landscape of the region, demarcating land uses and defining places of human occupation and settlement.

Spanish Settlement Policies

The general region designated as *El Reino del Nuevo México* was expansive and its boundaries indeterminate, but the first Spanish communities were established along the more confined *Río del Norte* corridor north and south of Santa Fe from Taos to Socorro either on the present day Río Grande or some of its tributaries (C. Cutter 1995). These settlement practices concerning location generally adhered to the ordinances set out in the Laws of the Indies and issued by the Spanish crown to colonial officials as instructions governing the pacification, development and permanent occupation of newly discovered lands, the *Ordenanzas de Descubrimiento, Nueva Población de las Indias dadas por Felipe II en 1573* (Crouch, Garr, and Mundigo 1982). Codified in 1681, the ordinances in the Laws of the Indies provided the framework for colonists and provincial governors to follow when selecting sites for occupation and development.

An important element in the ordinances was that fact that Spanish settlement planning through these instructions was environmentally guided from the outset (Arellano 1997; Carlson 1990). The ordinances, for example, instructed officials and colonists to establish settlements in sites with access to plentiful supplies of clean and pure waters for irrigation and domestic uses. In addition, the lands and the surrounding environments should be replete with the natural resources necessary to sustain permanent colonies: forests to supply fuel wood and building materials, abundant pasture lands for the grazing of livestock, lands with healthy and fertile soils for the cultivation and harvesting of crops, and a sky with clean, benign and pure air without impediments or alterations (Arellano 1997; Crouch, Garr and Mundigo 1982).

Throughout the period of Spanish settlement, colonial officials for the most part complied with the necessity of locating villages in places where reliable water supplies could support the permanent occupation of the province and thus secure the northern Spanish borders. As noted by Carlson (1990), agrarian planning reflected strongly the environmental realities of the settlement region, where rough terrain, aridity and high altitude limitations on the growing seasons necessitated an integrated approach to colonization. Spanish officials overcame these physical

barriers, Carlson and others argue, by implementing a wide array of land grant policies on the Río Grande watershed and its short but numerous perennial streams. In the case of communal land grants, for example, settlers petitioning for lands were required to specify the physical boundaries of the desired grant of land. Significantly, the boundaries of the land grants were not predetermined according to any formal grid plan, and instead were established according to the natural contours of the land, resulting in irregular shapes highly adaptive to local topography, vegetation, soils, hydrology and microbasin climates (MacCameron 1994; Van Ness 1987; Scurlock 1998).

In the next step, the governor would order an inspection of the boundaries to be conducted by the *alcalde mayor* of the jurisdiction. This official had to ascertain that the land in question was not already settled nor prejudicial to the welfare of any existing Indian Pueblo or other Spanish land grants in the vicinity. Part of the investigation on-site also included an evaluation of the water supply needed for irrigation and domestic uses, and for the watering of livestock (Baxter 1997). Further, the *alcalde mayor* made sure that the land, water and other natural resources within the boundaries of the grant would encourage tilling of the land, the grazing of cattle and other elements essential for permanent occupation (Keleher 1929). Absent any legal protests from adjacent Indian Pueblos or other neighboring communities with potential claims on the existing resources of the area, the governor would then be free to confirm the grant and authorize that the *alcalde* place the settlers in possession of the designated lands.

As part of the possession activities, each petitioner would be allocated a *solar de casa* for a homesite and an accompanying *suerte*, an irrigable parcel with boundaries laid out in a spatial arrangement consistent with the topographical and hydrological character of the watershed. The width of these individual tracts varied from site to site, dependent on local physical conditions and an estimation by the *alcalde* as to the size and configuration of bottomlands necessary for successful cultivation (Carlson 1990; Wozniak 1987). This unique farming landscape integrated each farm unit into the lay of the land and the watercourses for irrigation. The *tiras*, elongated long lots that resulted from partitioning, provided each land grant family with access to the fertile bottomlands and river banks, an essential aspect of gravity flow, communal equity and social organization (Rivera and Peña 1998; Carlson 1990). Similarly, all families would have access to the *ejidos* or common lands in accordance with the Spanish laws and local customs of the times. In these open lands, native pastures and forested areas typically surrounding the land grant community, villagers could freely graze their livestock, gather wood, harvest native plants and berries, hunt for wild game, and engage in other collective use privileges (Tyler 1989).

After the partitioning of the land, the settlers began the process of forming their community. Though the Spanish planning precepts for town layout and physical design were followed loosely—adapted to local conditions and resources—the upstream boundaries of each village were usually designated according to the place where the stream source was diverted and a dam installed. As part of the initial inspection, when needed, the *alcalde* would help locate suitable places where one or more ditch diversions could feasibly be

built to take water from the river source (Carlson 1990; Wozniak 1987). Once determined, this *saca de agua* (the diversion dam) was the first public works construction project undertaken in the formation of most communities, begun even before the building of the local mission or church.

On larger streams, such as the *Río del Norte*, the settlers built wing dams protruding into the river from one of the banks; these simple structures were usually sufficient to channel water into ditches during the irrigation season when natural flows were highest. Streams with intermittent flows, on the other hand, required the construction of dams across the width of the watercourses in order to impound portions of the flows and form small reservoirs. The *presas* (diversion dams also called *atarques*) were constructed of forest timbers, juniper brush, boulders, rock slabs, earth and other local materials, resulting in structures that often resembled beaver dams. These building materials were placed on the streambed in a layered fashion gradually raising the level of impounded water closer to a ditch headgate constructed on the banks of the stream. Containment of the water by the *presa* would accomplish the rest of the task, with gravity flow pushing the water into and through the main irrigation ditch or *acequia madre*.

To complete the infrastructure for irrigation, the *pobladores* excavated the *acequia madre* off one or both banks of the river, thereby extending the irrigable lands adjacent to the watercourse for several miles downstream. Typically, each *acequia madre* was cut perpendicular to the stream source at the upper end of the community in order to then convey water downstream, parallel to the river alongside the foothills or natural slope of the terrain, all the while enclosing the practical limits of irrigable land. Then, at the bottom end of the community the ditch was made to return to the original stream source through a *desague* channel.

Each commons ditch, described in the Spanish of the times as the “*acequia de común*,” was the main force that established a distinct place, defined the community boundaries, and bonded the irrigators obligating them all to the collective management of the local water system and their village enterprise as a whole. The idea of a common property ditch for all irrigators in any new settlement was replicated time and again in the province and, in fact, was the key to both the development and economic survival of local communities. As Tyler (1989, p. 26) vividly describes, the officials who placed the grantees in legal possession of the community grants made sure that the settlers acknowledged their rights and responsibilities to the common welfare “by swearing *de mancomún* or *de mancomunidad*,” meaning that they agreed to “work together for the benefit of the community and jointly manage their common property.”

Land and Water Petitions

Spanish colonization policy, thus, resulted in the building of communities alongside the *Río del Norte* and its tributaries in both westerly and easterly directions, further and further from the main stem of the river, eventually dispersing the population into numerous *plazas*, *ranchos*, *villas*, and other water-based colonies. Access to irrigation water served as the guiding principle, a continuation of land policy implemented from the outset since the founding of the early *villas*: San Gabriel in c.1600, Santa Fe in 1610, Santa Cruz de la Cañada in 1695, and Albuquerque in 1706.

When Governor Don Diego de Vargas proclaimed Santa Cruz in 1695 as the next *villa* after Santa Fe, for example, he did so because of the known fertile soils and plentiful supply of irrigation water available at the valley area known as La Cañada (Baxter 1997). By 1696, newly arrived families from Zacatecas and Mexico City could no longer be supported by the acequias and cultivated fields irrigated by the *Río de Santa Fe* at the capital city. Additional water and land resources would be needed to accommodate the growing population of the province. In his 1696 decree allowing a second group of Spanish-Mexican families to move to the Santa Cruz land grant, De Vargas assigned to them the use of the agricultural lands, irrigation ditches and dams, built at his expense, as well as access to the natural resources within the La Cañada environs. The decree by De Vargas illustrates the Spanish colonial precepts for town site planning, common lands use, and the reciprocal interdependence of land grants, irrigation, and the formation of community in the acequia culture that was emerging in the fledgling province:

Having recognized that in this villa of Santa Fe there is not the supply of water which is requisite to insure the irrigation of the cultivated fields, in order to maintain the families domiciled thereon; and having recognized that this said villa [of Santa Cruz] has better accommodations ... I assign them to said villa for the aforesaid reason.

I, the said Governor and Capitan General, have decided to go personally to the said Villa Nueva de Santa Cruz ... to examine the lands, whose sections are uncultivated, being naturally fertile, and being under irrigation as they are, and able to use the water which the rest have had generally in great abundance, assured by their ditches, clean and running, which have been established at my own expense, as I have also repaired and made their dam secure.

...likewise this will serve them as a patent to be residents belonging and assigned to the said Villa Nueva de Santa Cruz, and as such will further their use of the said lands, and their right to the pastures, woods, waters and minerals, as it appears in the [land] grant made to the said Mexican residents of said Villa Nueva, and that the said order made in their favor will be sufficient title for the privileges derived from the grant that I, the said Governor and Capitan General, have assigned to them in the name of his majesty (De Vargas Decree 1696).

Expansion of settlements to the upper reaches of the *Río del Norte* and to other basins frequently resulted from petitions by groups of restless *colonos* (colonist settlers) for more land and water to support the growing population in the uplands region. These petitions enabled the *pobladores* to respect the carrying capacity of the land and watershed streams they believed were already fully developed and appropriated. Repeatedly, groups of settlers took initiative to branch out in search of new territories just when the local natural resources, especially irrigation water from the rivers and creeks, began to show signs of stress. By around 1800, there were some 164 community ditches in the province, a number that would continue to grow at an even faster rate during the late colonial and the start of the Mexican period of land grant concessions (Hutchins 1928). Population growth and policies in support of colonization prompted *hispano mexicanos* to seek new lands for development well into the Mexican period. Availability of water was always of paramount concern. In 1837, for example, a group of *vecinos* (citizen residents) from the Valle de Santa Gertrudis (Mora) petitioned the *alcalde* at Las Trampas for additional lands a

few miles to the east, permitting them to take possession of the Guadalupita Valley on the *Río del Coyote*, a tributary of the Mora River. The petitioners proclaimed that new cultivable lands were necessary to sustain themselves and their families due to the scarcity of water at their current location in Mora:

We, the citizen colonists, among your Lordship's proven subjects, upon finding ourselves very cut back in water supply at this current place of residence, appeal to your kindness in the name of God and his divine laws, if you could be magnanimous and grant us the right to take possession of the Valley of Guadalupita, at the Coyote River, to cultivate and sustain a settlement there.... [To sustain] our families and in all reverence to the nation, with dignity, please accept our stated need with the list [of petitioner names] attached so that you may know the number of individuals that we submit for your kindness, and that is why we place this request to see if you can serve in the name of Justice to decree your wishes (Petition to Take Possession of Valle de Guadalupita, 1837).

The *alcalde* of the jurisdiction, Juan Nepumuseno Trujillo, acknowledged their petition and requested that the *colonos* appear before him within a few weeks of that same year, clearing the way for the eventual approval of the new settlement at Guadalupita and subsequent river communities downstream on the *Río del Coyote* (Lower Coyote, Lucero, and El Llano del Coyote, now Rainsville).

Social, Political and Ecological Values

Besides performing their irrigation function, the acequia waterworks have served other equally important roles: social, political and ecological. As a social institution, the acequia systems have preserved the historic settlements and local cultures spanning four major periods of political development: Spanish Colonial (1598-1821), Mexican (1821-1848), Territorial (1848-1912), and New Mexico Statehood (1912-Present). Politically, most acequia villages continue as unincorporated entities. In most places, the irrigators and their acequia associations serve as the only form of local governments below the county level. In the New Mexico portion of the region, these associations have been recognized time and again as political subdivisions of state government, a legal status similar to that of counties, townships and school districts (Report of the Attorney General of NM, 1963-64). More recently, the federal government has also recognized the acequia associations as public entities. In the Water Resources Development Act of 1986, Congress directed the Army Corps of Engineers to help restore and preserve the acequia engineering works and to enter into agreements with the acequias themselves as the local sponsors of the projects (Public Law 99-662). By 1996 these cooperation agreements had resulted in fifty-two contracts with local acequias for the financing of forty-nine ditch rehabilitation and diversion projects amounting to 14.2 million dollars in federal funds (Annual Report, SEO/ISC, 1996).

General maintenance of the community ditches continues to be a responsibility of the acequia officers and *parciantes* (the irrigators). The annual *limpia* (cleaning) of the acequia not only marks the beginning of the agricultural season in early spring, it is also an occasion for the *vecino* irrigators to

address local issues, reconfirming the traditions and values that undergird the social and political life of the community. During this ritual event, the ditch officers and irrigators, informally or in small groups, may address a broad range of topics such as the condition of the *presa* in the river, any repairs that might soon be needed, the amount of projected water flows based on the winter snowpack at the *sierra* headwaters, and other items of importance to the ditch or to the community as a whole. By the end of the ditch cleaning process, the irrigators have dutifully renewed their attachment to the land base of their own particular locality, assuring the continuance of place for yet another cycle of irrigation.

Recently, bioregional studies have documented that these earthen waterworks serve ecological and other purposes that should also be recognized by the public. Acequias, for example, extend the riparian zone, preserve farmland and rural open space, increase local biodiversity and protect the hydraulic integrity of the watershed. According to research conducted by Devón Peña and his colleagues, acequia landscapes in the San Luis Valley of Colorado and throughout the upper Río Grande double as important biological corridors and habitat islands for many species of plants and wildlife (Peña 1997). Conservation biologists, per Peña's analysis, might say that the acequia human community becomes the "keystone" species in the bioregional environment because numerous other life forms, wild flora and fauna, become dependent on the expanded habitat made possible by the ditch watercourses (Peña 1997; Noss 1994).

The beneficial impacts of acequia irrigation methods on the landscape, hydrology and the local ecology are many. For example, the earthen acequia watercourse itself helps to recharge the local aquifer through the natural process of seepage. Aided by gravity flow, water that continues to flow through the ditch extends the stream to a new, wider landscape; meanwhile, the water moves gently through the ditch and its *sangrías*, a process that spreads water slowly through the long-lot fields, helping to retard soil erosion. Water that percolates down to the aquifer aids in the cleansing of groundwater. Seepage throughout the ditch system nourishes the cottonwood bosques as well as native shrubs such as plum, chokecherries, willows, and other native plant species which, in turn, provide corridors of shelter, cover and food sources for wildlife (Peña 1997). Any unused waters are returned to the stream as *sobrantes*, or surplus waters, destined for other beneficial uses downstream.

Putting stream waters to beneficial use through acequia-based farming can also help to maintain instream flows for the protection of fish habitats. Both of these uses need not be viewed as conflictive, one at the expense of the other. Instead, they can be viewed as relatively compatible in the sense that they each require a minimum flow or otherwise sufficient hydraulic head of water in the river, as long as there is adequate quantity for both uses. Other water use alternatives, especially water-rights transfers from surface use to groundwater pumping, deplete hydrologically connected stream flows. This application can result in the lowering of the flows to levels potentially adverse to fish and other wildlife dependent on river systems that are wet year round. Acequia systems, on the other hand, contribute to the health of the river by flushing silt and taking surface water in the season when it is available, as opposed to

groundwater pumping, which most often creates deficits of water quantity by depleting the aquifers well into future years.

Stewardship and Environmental Ethics

The Spanish institutional framework for arid-lands irrigation has survived essentially intact into the modern era of agropastoral farming on the upper Río Grande. Unlike the fate of the community ditches in San Antonio, Texas, where the once indispensable network of mission acequias has been destroyed or reduced to tourism sites as remnants of the past, the acequias of northcentral New Mexico and southern Colorado continue to function in the traditional manner. Around the globe, the traditional and political rights of land-based peoples are increasingly threatened by demands placed on the limited resource base critical to the survival of local cultures. But there is growing evidence that countries in both the Third World and the West are giving serious attention to alternative models of development that emphasize community-based conservation and the utilization of the many reservoirs of indigenous and traditional knowledge. In the field of development administration, for example, planners and other officials now propose that cultural diversity itself is a global resource that should be preserved alongside the need to maintain and protect biodiversity (Kleymeyer 1996; Berkes and Taghi 1989; Redclift and Sage 1994). Customary rights and local traditions need not be regarded as impediments to rational water management; instead, modern legal systems should be redefined to co-exist with customary practices and thus achieve optimum resource utilization (S. Clark 1990).

After four hundred years of successful adaptation, the acequias of the upper Río Grande are model institutions worthy of further research. A good starting point is to consider the conservation ethics and environmental values that acequia irrigators inherited and transplanted from Old World irrigation systems. In his study of medieval Valencia, Spain, Glick (1970) found that the basic irrigation unit in the society was the *comuna*, a unit he defined as a group or community of irrigators all irrigating from a single main canal. These *comunidades* were instruments for self-government in the water affairs of local society; and by way of ordinances, they provided for the maintenance of the canal, authorizing the local *cequier* (official similar to the ditch boss or *mayordomo* in New Mexico and Colorado) to impose fines in cases where water was being wasted or polluted through unauthorized uses (Glick 1970).

Water quality protection and conservation were likewise taken seriously in the *acequias de común* that flourished centuries later in the upper Río Grande, carrying forward the water ethic evident in the irrigation societies of medieval Spain. In his review of customary practices transplanted from Spain to New Mexico, Malcolm Ebright (1994) noted that the environmentalist ethic was woven directly into the very fabric of custom and public law in the Spanish and Mexican land grant communities. A 1705 decree by Governor Francisco Cuervo y Valdez, Ebright points out, mandated that villagers of Santa Fe should not drive their livestock onto a marshy wetland and public commons known as the *cienega*; anyone who violated this order would face a jail sentence. These orders were repeated by subsequent

governors such as in 1717 when the village pigs and other loose animals were rounded up to prevent damage to the planted fields and the grass meadows found at the *ciénega* commons (Ebright 1994).

Guided initially by Spanish and Mexican water laws, the early settlers were mindful of conserving the resource base for themselves and for future generations, especially when the existing water supply could no longer support additional community growth. As mentioned earlier, petitions for additional land grants were submitted to the authorities with admirable regularity as population densities and the need for increased agricultural productivity outstripped the carrying capacity of the land base. After the new lands were occupied, irrigation practices were regulated in a manner designed to conserve the scarce water supply in each farm village. During the Mexican period, the Provincial Statutes of 1824-26 authorized local *alcaldes* to impose a one *peso* fine, plus the costs of repairs, on any irrigator who caused the flooding of roads and fields by not closing off his ditches when they overflowed (Provincial Statutes 1824-26). The first comprehensive acequia statutes were adopted in 1851 and 1852 at the start of the territorial period in New Mexico (Laws of 1851-52). Here again, water conservation was mandated. Section thirteen of these water laws stipulated that the *mayordomo* (ditch boss or superintendent) should apportion the available waters to each particular irrigator, but not only according to the amount of cultivated land he owned; the *mayordomo* should also take into consideration “*la naturaleza de las semillas, cosechas y de las legumbres que se cultivan...*” (the nature of the seeds, crops and plants to be cultivated...). Furthermore, each irrigator was entitled to retain all native plants of any description growing naturally on the ditch banks bordering and running through his property (Laws of 1851-52).

Other territorial laws specifically addressed the need to maintain water purity and quality in local ditches. In some ditches, *mayordomos* were authorized to levy fines against persons who befouled acequia waters by washing dirty clothes, bathing, or allowing swine to wallow inside the ditch (Laws of 1868 and 1872, cited in I. Clark 1987). By the turn of the century, a series of general, anti-pollution water laws had been enacted (1880, 1897, and 1899) that applied to all acequias of the territory. These laws prohibited the pollution of streams, lakes, and ditches by any number of means or the discarding of objects that would endanger the public health of the community. The penalties, upon conviction, were gradually made more severe, up to one hundred dollars and/or a sixty-day jail sentence in the 1897 laws (cited in I. Clark 1987).

Dividing and Sharing the Waters

Water conservation became a frequent concern in the late nineteenth century as the number of ditches and irrigators increased in some of the more densely populated valleys. The solutions and arrangements for the sharing of available water were primarily of local design, either by custom or legal agreements on how to divide the water, practices that continue to the present either intact or in some modified form. Some localities divide the water according to fractions where each ditch is entitled to its prorated amount of water, such as a one-third share in the case of three acequias

sharing the water in equal parts out of a common *compuerta* or headgate at the stream source. Other arrangements divide the water based on a scheduled time rotation, as in an 1895 example where ditches located in two Taos precincts agreed to take water from four streams in their area according to a predetermined weekly schedule. One precinct would be entitled to all the available water flowing in the four streams for their exclusive use and benefit from Friday of each week at sunset until the following Sunday at twelve noon; the second precinct thus, would take the water the rest of the time, from Sunday at noon until sunset on Friday. Per the terms of the agreement, this rotation plan would be repeated through the remainder of the irrigation season, lasting until the fifteenth of September every year (Agreement to Divide Irrigation Waters 1895).

During periods of drought or low water flows in the river source, most local acequias strongly value their customary practices of sharing, setting aside any legal rights based on prior appropriation. In many watersheds, acequia irrigators prefer the *repartimiento* system of dividing water according to local customs and traditions, where water is shared by all users, regardless of priority dates. Under these arrangements of customary usage, irrigators divide water based on historic practices of sharing and the need to provide *auxilio* (emergency mutual aid) during times of shortage or drought. This time-honored system of reciprocal assistance runs counter to the prior appropriation doctrine which forces a system of hierarchy among acequias and users who share the same stream source. Acequia officials and the *parciantes* as a whole are aware of this conflict, but most opt to ignore the strict system of priority calls on the river and would rather continue to share the water in the traditional manner (see Adjudication Hearings 1991).

This obligation to offer *auxilio* in times of special need and to share water during conditions of drought continues to be a deeply held belief of the acequia irrigators, an influence perhaps from the Moorish traditions evident in Spanish water law. According to I. Clark (1987), the Islamic law of thirst granted free access of water for all living things to satisfy their needs in the aridity of the north African homeland. “Islam not only subscribed to a belief in the purifying character of water ... but also the moral obligation of each to help all others of the community in the time of need” (I. Clark 1987, p. 9). Or in the words of a Taos *parciante* at the adjudication hearings on customs and traditions held in 1991 by Special Master Frank Zinn: “When [the flow is] low, nobody has any. When it’s high, everybody has some. That’s the way it was too. If there’s a cup of water there, we will share it” (Adjudication Hearings, Testimony of Esequiel Trujillo, May 20, 1991).

Repartimiento, water rotation schedules and other devices of sharing water have continued as local practices into the contemporary period, evidence of the persistent conservation ethos among acequia *parciantes*. Often, water rotations are established where individual irrigators from a single ditch are assigned certain days and hours of the week when it is their turn to take water from the ditch to irrigate their fields and gardens. Ditch rules provide for stiff penalties should an irrigator take water out of turn. Rules have also been crafted by the users themselves to protect and enforce water quality standards in the ditch. Just before statehood in 1911, for example, the *parcionistas* (landowner

irrigators) of the Margarita Ditch in Lincoln County charged the *mayordomo* with enforcing the “*Reglas de Limpieza*,” (Rules for Cleanliness). The Margarita Ditch Rules prohibited anyone from discarding junk in the community ditch, namely, “*garras, cajetes, puercos cueros, barriles o otras porquerillas que sean en perjuicio de la salubridad de los ha[b]itantes*” (rags, tubs, pig hides, barrels, or other filthy objects which might endanger citizen health).

Acequias and Contemporary Public Policy

The goal of Spanish settlement during the colonial period was to inhabit the vast reaches of the province based on agropastoral economies, a land use practice resulting not in the establishment of *municipios* (municipalities) but in the dispersal of the population throughout the rural jurisdictions of the region (Tyler 1990; Simmons 1969). Within the confines of available resources, some physiographic limitations, and many opportunities for creative engineering, the early *pobladores* proved adept at implementing the goals of colonization expressed in royal Spanish ordinances and subsequent Mexican land grant concessions. With the active encouragement of government officials who liberally implemented Spanish and Mexican land-distribution policies, the *hispano mexicano* settlers established permanent communities throughout the narrow valley bottomlands of *La Provincia del Nuevo México*. Acequias have withstood the test of time and insured the survival of a unique regional culture into the twenty-first century. These water institutions have operated with a few basic rules based on customs and traditions managing communal property resources with minimal government interference or assistance, features they share with other small-scale irrigation organizations around the world: the *subaks* of Bali, the *zanjeras* of the Philippines, the *sociedades de riego* in the Tehuacan Valley of central Mexico, and the *huertas* of Valencia, Spain. (Ostrom 1990; Berkes and Taghi 1989; Whiteford and Henao 1980; Maass and Anderson 1978).

In the upper Río Grande, the benefits of acequia-based farming extend well beyond the consumptive needs of the irrigators themselves. Watershed studies have established that acequias also help to maintain other important social, cultural, economic and environmental values that should be recognized by downstream water stakeholders, policy-makers and the general public:

1. The acequia culture of the region promotes tourism and economic development;
2. Protection of the acequia system of agriculture also protects the health of rivers, forests and the watershed headwaters in the sierra peaks;
3. Acequias promote a land ethic supportive of responsible stewardship of the watershed ecosystem in a high altitude, arid lands environment;
4. Acequias double as wildlife habitat and travel corridors, and therefore promote both wildlife and plant biodiversity; and
5. Acequia associations are democratic institutions that are dynamic, self-reliant and sustainable forms of local government (Rivera and Peña 1998; Rivera 1996).

Comparatively, the upper Río Grande community acequias of southern Colorado and New Mexico stand apart from the fate of many other irrigation canals in the western United States. In Worster’s historical study (1985), most irrigation systems in the American West have succumbed to the forces of the new hydrologic society, where water has been reduced to a simplified, abstracted resource, separated from the earth in a manipulative relationship with nature:

The modern ditch is lined along its entire length with concrete to prevent the seepage of water into the soil; consequently, nothing green can take root along its banks, no trees, no sedges and reeds, no grassy meadows, no seeds or blossoms dropping lazily into a side-eddy. Nor can one find here an egret stalking frogs and salamanders, or a red-winged blackbird swaying on a stem, or a muskrat burrowing into the mud. Quite simply, the modern canal, unlike a river, is not an ecosystem (Worster 1985, p. 5).

The earthen acequias of the upper Río Grande are unique in the western states. The *acequias de común* continue to function much as before, as model institutions of water management in environments where water is not plentiful and where reciprocal relationships of mutual aid are increasingly necessary if the human, animal and plant communities are to survive in balance and harmony. These keystone acequia villages perpetuate cultural continuity, a sense of place, and an indigenous system of participatory democracy that is worthy of public support as we enter the twenty-first century and already are confronting the challenges and opportunities of a pluralistic, diverse society of competing and often conflictive values.

Fortunately, values and perspectives concerning water resources policy are changing, especially in the American West where the era of large scale water development projects, meant to harvest and channel water destined for urbanizing regions or to reclaim desert lands for agribusiness welfare, is rapidly ending. Most river streams are fully appropriated or committed to the delivery requirements of interstate compacts and binational treaties. Thus, a new conservation ethic is taking root, but so are water markets and other mechanisms to transfer water away from historic or traditional uses in order to accommodate population growth, industrial development, recreational uses and other demands. These “higher use” values increasingly threaten the ability of acequia irrigators to compete on even terms. In Colorado and New Mexico water rights can be severed from the land and sold in the marketplace much like other property commodities. Some of the competing stakeholders perceive the acequia institution as antiquated and an obstacle to growth and development. To the critics, the acequia methods are wasteful and too primitive for the needs of a modern economy based on new industries, corporate agriculture, municipal growth and recreational tourism.

The challenge to acequia users is to retain ownership of their ancestral water rights in the face of mounting pressures to sell or otherwise transfer water rights out of the community. Not only must they continue to put their water to beneficial use, to avoid forfeiture, but in most cases they must also increase production, raise incomes and generate economic returns sufficient enough to discourage sales and transfers. Already, some ditch associations experience difficulties when it comes time to clean or repair the ditch waterworks. Maintenance of the system requires full and sustained participation from all *parciantes*, whether they

farm or not. Acequia officials fear that one water transfer from within the group of irrigators will lead to others, creating a domino effect, leaving fewer and fewer *parciantes* to maintain the ditch, raise funds for the seasonal repairs, enforce and administer the rules, and generally keep up with the chores of organizational maintenance. A collapse of the acequia institution would be catastrophic to the community and perhaps the surrounding area (Rivera 1996).

The event of the *cuarto centenario* provides an opportunity for all stakeholders and public officials to reflect on the historic and cultural values intrinsically connected to traditional water uses in both the Hispanic and Pueblo Indian communities. In the long run, sustainability of water quantity and quality may depend more on democratic and social processes than on technological or regulatory fixes. Understanding, dialogue and new ways of sharing are imperative. The four hundred years of acequia customs, traditions and values have endured and passed the test of time thus far. The pressures of the water markets in the bioregion have surfaced new realities creating tensions and conflicts across the myriad of users and stakeholders, and within the acequia communities themselves. Survival of the acequia institution depends on how adeptly the irrigators and their officers respond to these challenges and chart a course of action into the 21st century.

References

- Adjudication hearings on customs and traditions, transcripts. 1991. In: State of New Mexico vs. Eduardo Abeyta and Celso Arellano, and others, United States District Court for the District of New Mexico, May 20, 21, and June 11, 1991.
- Agreement to divide irrigation waters, Acequia Madre del Cerro and Latir Ditch. 1895. In: Rivera, José A. 1998. *Acequia Culture: Water, land, and Community in the Southwest*. University of New Mexico Press, Albuquerque, pp. 178-180.
- Annual report of the New Mexico State Engineer Office/Interstate Stream Commission. 1996. Santa Fe, NM: Office of the State Engineer, p. 47.
- Arellano, Juan Estevan. 1997. *La querencia: La Raza bioregionalism*. New Mexico Historical Review 72(1): 31-37.
- Baxter, John O. 1997. Dividing New Mexico's waters, 1700-1912. University of New Mexico Press, Albuquerque, pp. 1-2, 5-6, 12.
- Berkes, Fikret; Farvar, M. Taghi. 1989. Introduction and overview. In: F. Berkes, ed., *Common Property Resources: Ecology and Community-based Sustainable Development*. Belhaven Press, London, pp. 3-5.
- Carlson, Alvar W. 1990. The Spanish American homeland: four centuries in New Mexico's Río Arriba. Johns Hopkins University Press, Baltimore, pp. 4, 7-11, 23-37, 203-204.
- Clark, Ira G. 1987. Water in New Mexico: a history of its management and use. University of New Mexico Press, Albuquerque, pp. 9, 30-31.
- Clark, Sanford D. 1990. Tensions between water legislation and customary rights. *Natural Resources Journal* 30(3): 503-520.
- Crouch, Dora P.; Garr, Daniel J.; Mundigo, Axel I. 1982. *Spanish city planning in North America*. MIT Press, Cambridge, pp. 1-23.
- Cutter, Charles R. 1995. *The legal culture of northern New Spain, 1700-1810*. University of New Mexico Press, Albuquerque, p. 19.
- Cutter, Donald; Engstrand, Iris. 1996. *Quest for empire: Spanish settlement in the Southwest*. Fulcrum Publishing, Golden, CO, pp. 7-8, 54.
- De Vargas Decree. May 8, 1696. State Archives of New Mexico I, Translations, Archive No. 817. Santa Fe, NM: State Records Center and Archives. (For the De Vargas Proclamation, April 19, 1695, see Archive No. 882)
- Ebright, Malcolm. 1994. *Land grants and lawsuits in northern New Mexico*. University of New Mexico Press, Albuquerque, pp. 88-90.
- Glick, Thomas F. 1970. *Irrigation and society in medieval Valencia*. Harvard University Press, Cambridge, pp. 31, 35-37, 54-55.
- Hammond, George P.; Rey, Agapito. 1953. *Don Juan de Oñate, colonizer of New Mexico, 1595-1628*. University of New Mexico Press, Albuquerque, Vol. 1, pp. 17, 320-23, 346.
- Hutchins, Wells A. 1928. The community acequia: its origins and development. *Southwestern Historical Quarterly*, 31 (July 1927-April 1928): 278, 261-284.
- Keleher, William A. 1929. Law of the New Mexico land grant. *New Mexico Historical Review* 4(4): 352, 350-371.
- Kleymeyer, Charles D. 1996. Cultural traditions and community-based conservation. *Grassroots Development: Journal of the Inter-American Foundation* 20(1): 27-35.
- Laws of 1851 and 1852. *Territorial Assembly of New Mexico*. N.M. Revised Statutes and Laws (Studley 1865).
- Maass, Arthur; Anderson, Raymond L. 1978. *...And the desert shall rejoice: conflict, growth, and justice in arid environments*. MIT Press, Cambridge, pp. 11-45.
- MacCameron, Robert. 1994. Environmental change in colonial New Mexico. *Environmental History Review* 18(2): 27, 17-39.
- Margarita Ditch Rules. 1911. In: José A. Rivera collection, No. MSS 587 BC, Center for Southwest Research, Zimmerman Library, University of New Mexico, Albuquerque, NM.
- Noss, Reed F. 1994. A sustainable forest is a diverse and natural forest. In: DeVall, Bill, ed. *Clearcut: The Tragedy of Industrial Forestry*. Sierra Club Books/Earth Island Press, San Francisco, p. 37.
- Ostrom, Elinor. 1990. *Governing the commons: the evolution of institutions for collective action*. Cambridge University Press, New York, pp. 69-88.
- Peña, Devón. 1997. Cultural landscapes and biodiversity: the ethnecology of a watershed commons. In: Cabeza de Baca, Vincent, ed. *Hispanic Life and History*. Colorado Historical Society, Denver. Also see Devón Peña and Rubén Martínez, co-principal investigators, Upper Río Grande Hispano Farms Study, research project supported by the National Endowment for the Humanities, Grant No. RO 22707-94, Colorado College, 1994-1998. The documents and files resulting from this study will be archived at Colorado College.
- Petition to take possession of Valle de Guadalupita. 1837. In: Rivera, José A., *Acequia Culture: Water, Land, and Community in the Southwest*. 1998. University of New Mexico Press, Albuquerque, pp. 22-24.
- Provincial Statutes. 1824-26. Trans. Perrigo, Lynn I. 1952. *New Mexico Historical Review* 27(1): 66-72.
- Public Law 99-662. 1986. *Water Resources Development Act of 1986*, Section 1113, Acequias irrigation systems. Washington, D.C.: United States Congress
- Redclift, Michael; Sage, Colin, eds. 1994. *Introduction. Strategies for Sustainable Development: Local Agendas for the Southern Hemisphere*. John Wiley & Sons, New York, p. 11.
- Report of the Attorney General of New Mexico. 1963-64. Santa Fe, NM: Office of the Attorney General of New Mexico, Vol. 1: 247-252.
- Rivera, José A. 1996. Irrigation communities of the upper Río Grande bioregion: sustainable resource use in the global context. *Natural Resources Journal* 36(4): 743-44, 731-760.
- Rivera, José A.; Peña, Devón G. 1998. *Historic acequia communities in the upper Río Grande: policy for cultural and ecological protection in arid land environments*. Draft manuscript on file at the Julian Samora Research Institute, Michigan State University, Lansing, MI.
- Scurlock, Dan. 1998. *From the río to the sierra: an environmental history of the middle Río Grande basin*. USDA General Technical Report RMRS-GTR-5, pp. 105-119.
- Simmons, Marc. 1969. Settlement patterns and village plans in colonial New Mexico. *Journal of the West* 8(1): 7-21.
- Simmons, Marc. 1972. Spanish irrigation practices in New Mexico. *New Mexico Historical Review* 47(2): 135-150.
- Simmons, Marc. 1991. *The last conquistador: Juan de Oñate and settling of the far southwest*. University of Oklahoma Press, Norman, pp. 109, 114, 117, 148-49, 182.
- Twitchell, Ralph Emerson. 1925. *Old Santa Fe: the story of New Mexico's ancient capital*. Santa Fe, New Mexico Publishing Corporation, pp. 20-21.

- Tyler, Daniel. 1989. Ejido lands in New Mexico. In: Ebricht, Malcolm, ed. *Spanish and Mexican Land Grants and the Law*. Sunflower University Press, Manhattan, KS, pp. 24-35.
- Tyler, Daniel. 1990. The mythical pueblo rights doctrine: water administration in Hispanic New Mexico. *Texas Western Press, University of Texas, Southwestern Studies Series*, No. 91, El Paso, pp. 12-13.
- Van Ness, John R. 1987. Hispanic land grants: ecology and subsistence in the uplands of northern New Mexico and southern Colorado. In: Briggs, Charles L. & Van Ness, John R, eds. *Land, Water, and Culture: New Perspectives on Hispanic Land Grants*. University of New Mexico Press, Albuquerque, pp. 192-195.
- Whiteford, Scott; Henao, Luis E. 1980. Irrigación descentralizada, desarrollo y cambio social. In: *América Indígena* 40(1): 57-72.
- Worster, Donald. 1985. *Rivers of empire: water, aridity and the growth of the American West*. Pantheon Books, New York, p. 5.
- Wozniak, Frank E. 1987. *Irrigation in the Río Grande valley, New Mexico: a study of the development of irrigation systems before 1945*. Santa Fe, NM: New Mexico Historic Preservation Division, pp. 24-25, 64-65.

Resolving Resource Conflict: a Bigger Pie

Jim Winder

Abstract—One of today's critical questions for ranchers is how to gain economic benefits from natural resources without damaging biodiversity. Ranchers today face declining beef prices, escalating resource prices, and taking on costs once covered outside the industry. Ranchers join environmentalists and agency personnel in the struggle to meet evolving needs of the American people.

Change is inevitable but so is resistance to change. Ranchers, environmentalists and agency personnel are wrapped in a struggle over the changing management focus on public lands. Although this debate has many facets, the fundamentals lie in the evolving needs of American society. Lands once valued only for commodity production are now valued by a well fed public more for recreation and conservation. These changing needs and values have found their way into the market place where the real price of beef has declined precipitously and environmentalists are asking ranchers to pay the cost of past resource abuse. Paradoxically, the forces which seem to be destroying ranching on public lands offer the one legitimate opportunity for ranchers to survive on the land.

Ecology of Business

Just as plants and animal are subject to the laws of ecology, humans are subject to the laws of economics. A living organism must be able to out compete other organisms for natural resources in order to grow and reproduce. If that organism uses more energy than it captures, degrades its ecosystem, or is unable to compete for resources then it is not sustainable and will disappear over time. Business failures result from an inefficient process which uses more monetary inputs that it produces, degrades the resource or is at a competitive disadvantage with other businesses. To remain solvent a business must be sustainable in terms of Nature and in terms of the needs of society.

As the debate over proper uses of public and private rangelands continues in and out of the courts, only one thing is certain, economics will have the final word. Those uses of the land which are sustainable when all costs are considered will remain viable, however non-sustainable users will be pushed from the land. Far more ranchers will continue to leave the land because of economic reasons than because of the courts.

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Brief History of Ranching

To nineteenth century Americans, this country's vast rangelands held no value outside of commodity production. Domestic livestock grazing, at its core, is only a method to harvest and refine native vegetation which is indigestible to human beings. Grass had no value in and of itself, it was only when that grass was converted to beef that the value was realized. And thus the beef industry took root as a method of refining the vast natural resources in the American west.

The history of the western beef industry is not unlike that of many other industries, rapid growth and large profits which recruit additional producers which in turn lead to industry maturation. In the case of the beef industry, this aging process was escalated by a government policy of cheap food which encouraged further production through investment in research. On one level the research was successful as production per cow more than doubled. But on another level it was disastrous for those ranchers it professed to help, as production improvements only tended to flood the market with more tons of beef selling at lower prices. This policy was good for society and politicians as real food prices declined but devastating to the rancher as beef prices failed to keep up with inflation.

In 1960 it took 8 finished steers to buy a new pickup truck, today it takes 34. This shows us that the real price of beef has declined precipitously while the price of inputs has continued to climb. In real terms, American society values beef relatively less today than it has in the past. At that same time, society has begun to place value upon other, non-commodity, uses of natural resources such as conservation and recreation.

New Uses of Natural Resources

When my grandfather ranched, the price of a parcel of land was determined by its productivity in terms of livestock, timber or mining. In financial terms this meant that the price was approximately equal to the present value of the expected net income stream from these enterprises. In my father's time the price of land began to reflect a new value, recreation. A ranch would be valued higher if it had greater recreational potential, such as deer hunting, even though commodity production was comparable to other ranches. Today our society has found a third value for natural resources, that of conservation. Organizations and individuals purchase ranches with no intent of grazing cattle, instead they are focused on habitat production. Individuals value a parcel of land for its health, and are willing to fight for land that they have never even walked upon. It is the conservation value of our lands that fuels the entire environmental movement.

The ranching community which is suffering through the fall in real beef prices is now faced with escalating resource

costs due to the competition from non-commodity users. In other industries faced with maturation, the strategy is consolidation in order to reap economies of scale. Ranchers are denied this option because they are unable to pay for additional land through production centered on only one land value, when the land price reflects all three values.

Scarcity

Damage to the environment resulting from business activity is often not paid for by the business but born by society. Economists call this an external cost. Costs such as riparian deterioration or species extirpation do not show up on the financial statements of any company but instead are thought to impoverish society, especially future generations, through reduced resource productivity and the direct cost of remediation. The major strategy of the environmental movement is the reversal, or internalization of these external costs. That is to make the business pay for the true costs of production, not just labor and materials but the present and future cost of keeping the land healthy.

At a time when profits in the mature livestock industry are at a low ebb, ranchers are unable or unwilling to shoulder additional costs, whether real or perceived. Thus the heart of the debate for ranchers is economic survival. Proposals to restore riparian habitat or reintroduce wolves are feared for their perceived effect of reducing production and increasing costs. This attitude is one of scarcity, there is only room for commodity based businesses on the land, anything involving recreation and especially conservation will deplete commodity production.

An Alternative

Ranching is a capital extensive industry, that is it takes a lot of capital in the form of land, livestock and equipment to produce beef. Often a rancher has invested in excess of \$4000 for each animal unit grazed. Traditionally, the net return on asset (ROA) for ranching has hovered around 2-3 percent in the best of years. This is very low, considering the risk involved with a ranching investment and the fact that one could usually earn a higher return with a risk free government bond. When we view the simple equation for return on assets:

$$\text{ROA} = \text{Net Returns} / \text{Total Asset Value}$$

it is apparent that there are only two ways to improve ROA, increase the productivity of the assets in terms of net returns or decrease the cost of the assets required for a given level of production. We have seen the results of the industry's focus on increasing beef production with a never ending stream of innovations. A better way of increasing productivity is not to produce more of the same old thing but to produce new products from the same asset base. Since much of the price of natural resources is related to conservation and recreation, it is rational to base new products upon these values.

Raw values for natural resources are analogous to clouds. They are real and can be seen but they are impossible to grasp or to hold. They have no cash value in and of themselves but offer the possibility of creating wealth through

secondary products. Just as the rangeland grasses of the nineteenth century were worthless to humans until livestock converted them into beef, conservation and recreation values must be refined into products that can be marketed and consumed. For a rancher to survive and even prosper in the urbanizing west, the question is how to develop a range of compatible products which tap into all three natural resource values, commodity, recreation and conservation.

The answer to this question is two fold. The first requirement is for a rancher to evolve into a full resource manager with an understanding of the structure and function of the ecosystem. For decades range managers were taught what was good for cows and grass with little emphasis placed on other species or ecological processes. A resource manager should now have a working understanding of the interactions among species since it is this interaction which gives structure to an ecosystem. Also the manager needs to understand the multitude of processes which comprise the ecosystem function. These processes include recovery following disturbance and the distribution of water and nutrients throughout the landscape and the seasons. While the complexity of life on Earth insures that no individual can understand everything, proper management of natural resources necessitates a manager who knows the land. A resource manager who is able to keep the land healthy and sustainably produce goods and services which society values, will have a long tenure on the land.

Once expertise in resource management is gained, the next step is to develop the products and trade channels necessary for delivery to the consumer. Since commodity and recreation values have been around longer their markets are more well defined. A large infrastructure exists for trading commodities and the market is readily accessible to any producer. A broad and varied market exists for recreational products which usually take the form of an experience, a fishing trip, but may also include the tools which make the experience more enjoyable, a new rod. Since society has only recently begun to place significant value on the conservation of natural resources, products and market infrastructure are rare and unproven. Although this situation makes marketing somewhat more difficult, it rewards creativity and gives small businesses equal footing with larger concerns.

Conservation products will initially be marketed to governments and conservation organizations. This may take the form of land sales, grants or conservation easements. Often conservation may involve a service instead of a hard product. Many people are interested in the land but few understand how to manage resources. Opportunities abound for individuals to provide broad based managerial service. These managers need to be able to add real value to the resource by improving wildlife populations as well as the aesthetics such as riparian habitat. Other products and services will undoubtedly be produced and refined over time.

In contrast with a rancher who is trying to maximize production of beef from a finite set of resources, the resource manager's goal is to blend production from the three values in a manner which maximizes profit. To do this one must look for synergy between products which slash costs. An example is a recreational enterprise which is based on traditional ranch activities like branding and gathering cattle.

Conclusions

The greatest danger a rancher faces today is that the cow, once only a tool, has become a way of life, and end in herself. If ranching disappears as a viable use of natural resources it will be because of resistance to change, not an ability to evolve with the times.

Ranchers face three critical and permanent economic realities, declining real beef prices, escalating resource prices driven by conservation and recreation values, and the

internalization of costs once externalized by the industry. To survive, individual ranchers must become economically relevant and use the strong forces of change in their favor.

It is when the rancher evolves into a resource manager blending commodity, conservation and recreation values into sustainable products that they will truly understand needs and desires of other resource users. This common ground will be the foundation for a new industry that answers the critical question of how to gain economic benefits from natural resources without damaging biodiversity.

How Great a Thirst? Assembling a River Restoration Toolkit

Steve Harris

Abstract—The Rio Grande River's biologically troubled status is clearly linked to present and historic water management. To restore the river to pre-settlement conditions will take a "tool kit" that holds authorities, knowledge, and skills needed to correct historical neglect and abuse. Tools include awareness, planning, partnerships, engineering solutions, and a cross-section of public and private individuals.

In a presentation most of us heard earlier in the week, Steve Hansen from the Bureau of Reclamation showed us some data that leads, inescapably, to the conclusion that there is simply not enough water available to the Middle Rio Grande to continue to satisfy the kind of demands that are being placed upon the river. A few moments ago, Paul Tashjian from the Fish and Wildlife Service told us that the Rio Grande is in the process of "dying" biologically, a conclusion borne out by the facts:

- The status of small fish species in the aquatic ecosystem—all gone except for the endangered Rio Grande silvery minnow. Perhaps 23 aquatic species extirpated from the middle river.
- The decline of the Rio Grande riparian forest, as documented in the Bosque Biological Management Plan.
- The status of neotropical migratory birds—107 species in decline. In an accumulation of human induced impacts, some of this is no doubt attributable (at least in part) to a fragmentation of habitat in the Rio Grande Flyway.
- The fact that wintertime streamflows at El Paso contain such concentrations of total dissolved solids that the city doubts its ability to treat the water to drinking water standards.

The fate of human occupation, the sustainability of our communities, economies and cultures is directly linked to the river, not just as a water resource but also as the big, wet life support system that gave us birth.

Today, the river's status can be clearly linked to present and historic water management practices...the blunt fact that over the past 86 years, 98 percent of the water produced by Rio Grande watersheds gets consumed by the time the river reaches Hudspeth County, Texas. Not only do we

mercilessly use the river up, the future is likely to get worse. Consider:

- That in the present scramble to secure municipal water supplies, more than 100,000 acre feet of water that presently escapes as streamflow (~55 kaf of SJ-C water and ~60 kaf of wastewater from ABQ), may soon be diverted and consumed.
- That without an expenditure of public monies, the Middle Rio Grande Conservancy District will continue to divert 5 or 6 times more water than its crops consume.

In talking about "restoring" the Rio Grande, I want to make a couple of points as strongly as possible:

First, I do not propose that we can return the river to its pre-settlement conditions. "Restoration", as I am using the term, means restoring a measure of lost biological integrity and function. Nature had an irrigation and flood control plan which we must try to rediscover, because unlike our own plans, it let life exist. I'm embracing the term "restoration" because the current notions of "preservation" or "protection" will not ensure that we have a healthy Rio Grande in our future. That unless we can begin to reverse it, the present trend toward degradation will continue to its logical and unfortunate conclusion.

Second, the river needs irrigating. More than any other combination of factors, simply managing our water to mimic the way nature does it, is the first order of business, if restoration is the goal. We can't zero out the flows (and with 100 kaf of new diversions on Albuquerque's drawing board, an utterly dry river bed would appear to become increasingly likely), we must reconnect the river to its floodplain, providing periodic overbank flooding and we must shape our managed hydrographs in conformance with the natural ebb and flow conditions in which the river's biota evolved. We must understand and work in harmony with the river.

Third, the real issue in providing instream flow is not so much a question of acquiring an additional quantity of water (though some wet water will have to be dedicated from existing and planned uses), but more a question of improvements in the timing of flows.

Fourth, there is reason for optimism: the minnow had a good year in 1997, the whooping cranes have not left us entirely and all the players seem to be willing to acknowledge a problem. Our history of water management has been so haphazard that we can easily save 10 percent over present uses (and maybe a great deal more) if we can implement an integrated water conservation program.

Fifth, we cannot afford to fight about this very much. I do not propose to dismantle agriculture to save the river. Agriculture is under enough pressure without environmentalists sniping at it. Neither would I entertain a proposal to

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desiccate the river to preserve the status quo; it isn't working. We must learn to honor all aspects of our heritage: healthy ecosystems and healthy economies.

The bad news is that the Rio Grande, like the planet's biological systems in general is, in the words of the immortal Merle Haggard "*rolling downhill like snowball headed for hell*." The good news is that we can still avert the crisis. So we must cling to our hope and not give up, just yet.

My assignment today is to convince you that we have a sort of "tool kit", comprised of all the authorities, knowledge and skills which exist in this region to correct the neglect and abuse we have heaped upon a once-functioning river. In order to restore the Rio Grande, we will need them all.

In quenching our various and endless thirsts, we have become accustomed to putting the river at the end of the line. We have deluded ourselves into thinking that a river is nothing more than a supply of water, that the vested needs of downstream users guarantees that here will be ample water in and for the river and that our water rights (mere jottings on paper) equate to water itself. We will have to get over these delusions.

It is quite useless to point fingers for the shortsightedness of the past. Besides, there aren't enough fingers to complete the job. We believed what the engineers of 1890 told us about rivers and, to a lingering extent, act as if we still believe them, despite mounting evidence that nature had a terrific plan for delivering water.

Just as we have all had our roles in trying to conquer the river, so we can all be a part of its redemption. It is possible that we will avert the crisis without ever pointing any more fingers, but solutions will only come if we can deploy each of the following tools:

Awareness—Since we are aware that we have a critical problem that affects all of us, we must now make certain that none of our actions and none of our inactions is serving to perpetuate the problem. Each of us can and must employ the tool which is our own awareness...and insist that any who remain in denial come along with us.

I think we're beginning to see the end game on water in the Middle Rio Grande. If we wait to accept the great challenge until the crisis is actually upon us, we will have already lost—first the river, then the farm and then the house. There won't be any Animas River water or Lake Superior water or iceberg towing projects to bail us out. Another aspect of awareness is our understanding of how the Middle Rio Grande water system works, including the effects of our water manipulations on aquatic habitats. Despite some heroic work by Steve Hansen, the Bureau and the City, we still need to know more about the groundwater-surface water interface, project return flows, evaporation and transpiration from all sources. The Corps, in partnership with a number of agencies is developing URGWOM which promises to provide a look at the hydrologic effects of any number of water management scenarios. This sort of information is a valuable tool.

And the ability to do "adaptive management", develop and undertake practical experiments, monitor results and modify such efforts is an essential tool, enabling us to avoid that common pitfall, "paralysis by analysis".

Planning—Planning is a particularly powerful tool to the degree that it includes both economic and environmental

interests. The Fish and Wildlife Service put together an unprecedentedly diverse team to write the silvery minnow recovery plan: farmers, water users from upstream and down, along with the biologists and bureaucrats who customarily write recovery plans. In fact this was an experiment. Letting affected economic interests into the species recovery game had never been tried. A good theory, but I'm not sure that it worked; I'm not sure that everyone was fully engaged toward the main goal, which was to recover the minnow.

Now, we have the Middle Rio Grande Regional Water Planning effort, with 35 stakeholder representatives attending meetings. So far, it seems that the same sort of dynamic prevails: the large water users are watching and waiting and ready to bail out if the outcome doesn't exactly suit them. Right now, the regional plan is some distance from acknowledging all of the complexities.

Additionally, these sorts of plans need to have their implementation written right into them. Producing a document is only half the battle. As Bob Ohmart says: "when all is said and done, a lot more gets said than gets done". I sense, though, that everyone in the Middle Rio Grande is getting the idea that we really can't go on like this and that critical regional planning will eventually find its legs and begin to walk.

Partnership—It goes by many names: sharing the load, listening to the other person, fairness, reciprocity, cooperation, collaboration. Those of us who are, or have been, married know that this can be a hard tool to get sharp. Everyone has their own interests at heart and nobody can defend my interests better than me and mine. So part of partnership is being fierce in the defense of one's own interests; the other part is to respect the values of others. This is where partnership gets tricky. To work together requires that we have a common experience, interest or goal, which in this case is the sustainability of our communities, farms and ecosystems. In varying degrees and proportions we all do value and respect these things.

To answer the river restoration challenge, we must all be willing to consider viewpoints we are currently uncomfortable with. Today's paradigm for governance is that I can defeat my adversary's initiatives as easily as he can defeat mine. When gridlock ensues, everyone loses. The proper goal of partnership in the Middle Rio Grande is that no one loses. We may forego the "thrill of victory", but we will eliminate the "agony of defeat."

Plumbing—I'm going to suggest that engineering projects, the very tools that got the river into its present state may also serve to get us out of this mess. For example, there's 2-300 kaf of what appears to be federally-owned water, undelivered San Juan-Chama water in storage in Heron Reservoir. In 1996, it was proven that if the Bureau feels it has the authority to do so, it can pass water through El Vado, Abiquiu and Cochiti for environmental purposes. I must also point out that, once that water is in the river, it's going downstream to ring the bell at Elephant Butte and satisfy our obligation to Texas...unless, of course, it's intercepted.

We've also got this maze of canals and drains and acequias and subsurface seeps that is the MRGCD system. This is 75 year old plumbing, the inefficiencies of which are demonstrated by the fact that the District diverts 5 or 6 acre-feet

for each acre foot consumed by the crop. Chief Engineer Shah tells me that much of this excess is necessary to get enough head to push water through portions of the system, particularly the highline canals. This raises the possibility of reducing diversions by reengineering portions of the District's delivery system. Thus, the draglines and loaders and dozers so loathed by environmentalists could be a very powerful tool for restoring the hydrograph.

In putting forward our own Middle Rio Grande Plan, yesterday, an Alliance of river protection advocates suggested that we would be willing to lead, or join, an appeal to Congress for the very significant funding these sorts of projects will require.

People—Throughout the upper Rio Grande Basin, community members are demonstrating that they care very much about the future of the river. I'm pleased to note that Alamosa, Colorado and Socorro, New Mexico and El Paso, Texas each have major projects underway, each aiming to restore hundreds of acres of river banks and riparian wetlands to some semblance of a functioning condition. This tells me that thousands within the basin are willing to devote their energies to the river, against long odds. I wonder how many more would express their loving concern for the river if we could offer them strong hope of success?

I'm convinced that the majority of the 10 million folks with whom we share the Rio Grande possess some sense of the river's importance to the long term survival of our region.

I hope I've left you with my own sense that we have a lot of the tools we need: the incentive (survival), the engineering (water storage), the raw materials (remnant areas of biodiversity), the knowledge (or the means to acquire it)—to restore the Rio Grande. If the stakeholders, the City, the District, their ratepayers, the Bureau, the pueblos, the OSE/ISC, environmental groups and others, demonstrate that we can bite the bullet, accept the responsibility, sit down and tackle this together, then our legislative bodies will not deny us the financial means.

References

- Brookes, Channelized Rivers. Wiley, 1988
- Collier, and others, Dams and Rivers: Primer on Downstream Effects of Dams. USGS Circular # 1126, 1996
- Clark, Water in New Mexico: A History of its Management and Use, UNM Press, 1987
- Crawford, and others, Middle Rio Grande Ecosystem: Bosque Biological Management Plan. USFWS, 1993
- Daves, and others, City of Albuquerque Water Resources Management Strategy, 1997
- DuMars and Nunn, eds., Middle Rio Grande Conservancy District Water Policies Plan, 1993
- DeGraaf and Rappole, Neotropical Migratory Birds. Cornell, 1995
- Hansen, and others, Middle Rio Grande Water Assessment. USBR, 1997
- Petts and Calow, River Restoration. Blackwell, 1996
- Philippi, Floodplain Management-Ecologic and Economic Perspectives. Academic, 1996
- Rosgen, Applied River Morphology. Wildland Hydrology, 1996
- Whitney, and others, Rio Grande Silvery Minnow Recovery Plan. USFWS, 1998

Española/Canjilon Pilot Study: Economic, Social, and Cultural Aspects of Public Land Grazing on the Santa Fe and Carson National Forests

Carol Raish

Abstract—Many of the livestock grazing permittees on the Carson and Santa Fe National Forests in northern New Mexico are descendants of Hispanic settlers who have farmed and ranched in the region for 400 years. Much of the permitted land was formerly owned or used by local communities under Spanish and Mexican land grants. Cultural differences and historical issues of landownership and use contribute to disagreements between permittees and federal land managers. This study will examine current economic, social, and cultural aspects of livestock ownership by these permittees to help agency managers administer the lands with increased effectiveness by promoting greater cultural understanding.

Much of the current debate surrounding federal lands occurs because land managing agencies have failed to emphasize and monitor sociocultural values and changing attitudes toward land use and management. A comprehensive, nationally focused research project titled “Sustaining Rural Communities: Measuring Social and Cultural Diversity in Land Use” addresses the need to emphasize and monitor values and attitudes. A section of this project focuses on traditional livestock raising on public lands in northern New Mexico. The Española/Canjilon pilot study tests the northern New Mexico research design and implementation methods on the Española and Canjilon Ranger Districts of the Santa Fe and Carson National Forests.

Historical Background

To understand the complex issues surrounding livestock grazing on federal lands in northern New Mexico, it is necessary to understand the historical background of land use and ownership in this area. Many of the small livestock operations in northern New Mexico are owned by Hispano families, regional residents since well before the U.S. conquest in 1848. (Small ranches are defined here as those with less than 100 animal units yearlong—AUY. An AUY is the forage required to support a cow and a calf for 1 year; Fowler and others 1994: 2.) The Hispano ranching tradition began with Spanish colonization in 1598 but did not become fully

developed until after the reconquest of 1692 through 1696 (Earls 1985:179-181, Simmons 1979:182, Wozniak 1995). During the Spanish Colonial (1598-1821) and Mexican (1821-1848) periods, landownership and use were legalized or confirmed by land grants from the Spanish Crown or Mexican government.

There were several types of land grants. Community grants, used by a group of settlers in common (Eastman and others 1971:4, Harper and others 1943:18-19), are of particular interest because they are a primary landownership issue in the region. Within community grants, settlers received individually owned building sites in the village and plots of irrigated agricultural land. The irrigated plots, often averaging only 5-10 acres (Van Ness 1987:172), grew smaller when divided for inheritance. The villagers used the community grazing and timber lands and pastures in common (Eastman and others 1971:4). Since groups of kinsmen often tilled their fields cooperatively and herded their animals together on large tracts of communally owned land, they were able to survive on the small, scattered agricultural plots.

Conquest of the region by the United States in the Mexican-American War of 1846 through 1848 changed landownership and patterns of range use. Under the Treaty of Guadalupe Hidalgo, the United States was supposed to recognize and respect the property rights of former Mexican citizens. To obtain valid land titles according to U.S. law, however, land grantees had to petition for title confirmation. Although 128 land-grant claims and 19 Indian Pueblo grants were confirmed in the state, many claims were rejected (Eastman and others 1971:5, Eastman and Gray 1987:24). Often, house lands and small irrigated plots were confirmed, but the community pasture and woodlands, also part of the grant and essential to the survival of small farmers and herders, were not. Lands from unconfirmed claims reverted to the public domain (Eastman and others 1971:5, Eastman and Gray 1987:24). In addition, villagers lost significant amounts of confirmed land because they were unable to pay property taxes under the American system of monetary tax payment, which differed substantially from prior systems of payment based in animals and produce. Unscrupulous land speculation also occurred, which took advantage of Hispanic farmers who neither spoke English nor understood the American legal system (de Buys 1985: 171, 178-179). After passing through the hands of various owners, a large portion of the lost grant lands ended up in federal control. Currently, in north-central New Mexico, the Forest Service and the Bureau of Land Management (BLM) manage much of this land (de Buys 1985:171, 178-179, Eastman and others 1971:5).

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Relevance of Research on North New Mexican Grazing Issues

Many of the former grant lands came into federal control in degraded condition, often resulting from large-scale timber harvesting and large, commercial ranching operations that occurred after the land had been alienated from its Hispanic owners (Rothman 1989). The methods used to rehabilitate degraded land were sometimes thought harsh and poorly explained by local ranchers who graze their livestock on federal lands under permit (de Buys 1985:248-249). Since many of the northern grazing permittees are the descendants of grantees, many resent government restrictions and fees to use land they consider to be rightfully theirs.

Discontent over federal grazing policies, protest over lost grant lands, and general economic decline in the region led to violence in the 1960s. Protests by the *Alianza Federal de Mercedes*, led by Reies López Tijerina, culminated in the now-famous raid on the Tierra Amarilla courthouse in 1967. Two of the main goals of the group's actions were to bring the problem of massive land grant loss to world attention and to address a series of grievances concerning management of grazing on the national forests (deBuys 1985).

The violence of these protests led to reexamination of Forest Service policies in northern New Mexico. The Forest Service produced *The People of Northern New Mexico and the National Forests*, commonly known as the Hassell Report (Hassell 1968). The report recommended 99 measures, 26 related to grazing, to improve the situation of the Hispanic villagers. Some measures were implemented, additional money was brought into the region, and some progress was made. In addition, the Forest Service developed a special policy for managing the forests of northern New Mexico.

The Southwestern Policy on Managing National Forest Lands in the Northern Part of New Mexico, or the Northern New Mexico Policy, stressed the importance of valuing the Hispanic and Indian cultures of the Southwest (Hurst 1972). Policy implementation was based on the recommendations of the Hassell Report (1968). The Forest Service periodically reviewed implementation of the report recommendations. After the last review in 1981, the agency decided that a separate policy statement was no longer needed and that further implementation would be through regional and forest mission statements and plans (Hassell 1981).

Problems remain in the area and many of the conditions highlighted in the Hassell Report (1968) have not improved. Severe poverty, disappearance of traditional lifeways, and environmental degradation are still major concerns. Unfortunately, many Forest Service employees are unaware of the Hassell Report (1968) and the situations that led to its development. They receive no special training in the cultural traditions and social values of northern New Mexico. Significant misunderstandings persist, and the potential for conflict still exists. This likelihood is demonstrated by protest responses to an injunction against logging and fuel-wood harvesting to protect spotted owl habitat in 1995, hanging of two Santa Fe environmentalists in effigy at a protest rally in November of that year (McClellan 1995), and a bomb explosion at the Española Ranger District office in 1996. No one was injured by the blast, which did minor external damage, and no one has been arrested. This discussion does not imply

that Hispanic groups are responsible for the blast but indicates continued unrest in the area. Investigation of the incident is focused on recent controversies involving the Forest Service including environmental issues and disputes over fuel-wood gathering and grazing rights (Korte 1996, Ragan 1996).

Research Problem and Goals

This research project focuses on contemporary issues among the forest users of northern New Mexico to provide information and guidance to land managers. Understanding the role of small livestock operations in northern New Mexico communities is crucial to comprehending and resolving disputes over federal land and resource use. Thus, this research will examine the economic, social, and cultural contributions of livestock operations on the Carson and Santa Fe National Forests to rural Hispanic communities of the area. Local attitudes toward land management policy and sustainable resource use will also be examined, as will attitudes of Forest Service managers toward local issues. The outcomes of this study will include an inventory of contemporary community conditions that the Forest Service should monitor into the future, and development of reliable monitoring methods in a culturally diverse environment. These methods can ultimately be used to monitor conditions on other public lands with diverse user groups.

Elements to be inventoried and monitored include the following:

- a. Economic contribution of domestic stock to family and community income.
- b. Extent that public land use for grazing and other purposes allows communities to maintain social cohesion and traditional culture.
- c. Local perceptions of public land use and land management policy.
- d. Federal land managers' perceptions of local issues.
- e. Presence or absence of cultural differences in perceptions of sustainability and how to achieve it, and changes in these perceptions in response to agency programs.

The Española/Canjilon pilot study will evaluate and refine the research design and the proposed implementation methods on a portion of the study area.

Research Setting

The Española Ranger District was selected first for the pilot project because it is a good example of livestock operations on the Carson and Santa Fe forests. There are 9 active grazing allotments on the district ranging from ca. 7000 acres to ca. 73,000 acres. Excluding 4 small allotments, allotments range from ca. 4000 acres to ca. 100,000 acres on the Santa Fe Forest. All the Española allotments have more than 1 permittee per allotment, ranging from 2 through 16. Seventy percent of the 77 active allotments on the Santa Fe have more than 1 permittee, ranging from 2 through 20. Forty percent of the 71 allotments on the Carson have more than 1 permittee, ranging from 2 through 25. Multiple-permittee allotments, small herd sizes per permittee, and grazing associations of permittees demonstrate the continuing communal range use in northern New Mexico. Of the 17

listed grazing associations on the Santa Fe, 6 occur on the Española District. There are 24 associations on the Carson.

Herd sizes are generally small on the district and on the 2 forests. Of the approximately 55 people with Forest Service permits on the district, 30 have permitted head numbers from 1 to 25, 11 have 26 to 50, and 14 have 51 to 100 (of these, only 5 have over 70 permitted head). There are no operations with over 100 permitted head on the district. Española demonstrates the allotment pattern common to the north New Mexican forests, that of multiple permittees, grazing associations, and small herd sizes. (Information on range statistics from the Carson and Santa Fe National Forests was obtained from range data tables provided by Jerry Elson, Range and Wildlife Staff on the Santa Fe National Forest; Sylvia Valdez, Resource Assistant on the Santa Fe National Forest; Don Case, Range, Wildlife, Fish, Soil, Air, and Water Staff on the Carson National Forest; and Lorraine Montoya, Resource Assistant on the Carson National Forest.)

After discussions with range staff from both forests and with representatives of local user groups, I decided to broaden the pilot study by including a district from the Carson National Forest along with Española. The Canjilon Ranger District, with ca. 57 permittees, was recommended as a good example of livestock operations on the Carson (Don Case, pers. comm. 1997). Canjilon has 12 active grazing allotments ranging from ca. 300 acres to ca. 43,000 acres. Four of the allotments have more than 1 permittee (ranging from 3 through 25), while 8 have 1 permittee. The district's 4 grazing associations occur on the allotments with the largest numbers of permittees. The majority of herd sizes are from 4 to 250, with 7 operations having 100+ head. The largest herds per permittee occur on the single-permittee allotments. Canjilon provides some contrast with Española, having more single-permittee allotments with larger herd sizes, while still having many of the relatively small-sized livestock operations typical of northern New Mexico.

Española/Canjilon Pilot Study _____

The Española/Canjilon pilot study will develop baseline data describing economic, social, and cultural contributions of livestock operations to rural Hispanos in the late 1990s. This information will be useful for monitoring the role of livestock operations in the future. Some comparisons to previously collected information will also be made. Perceptions of public land use and land management policy, as well as federal land managers' perceptions of local issues, will be examined in the larger study conducted on the 2 forests. Future studies will also explore the possibility of cultural differences in perceptions of sustainable resource use and how to achieve it.

The pilot study assesses research questions that will guide the larger study, and the methods and techniques that will be used to collect information. Results of the pilot study will be used to evaluate and refine the research questions by developing new topics and questions, and by deleting inappropriate topics. Prior research indicates that livestock operations contribute economically, socially, and culturally to the owners' lives. Pilot study results will be examined to determine if new contributions should be added or if prior contributions have shifted in emphasis.

Contributions of Livestock Operations

Research on small-scale cattle operations in the 1960s and 1970s demonstrated that, although domesticated animals were important components of household economy, most of the small operators did not depend on their crops and animals for all their support. They generally had outside jobs or were retired. The livestock made many contributions to the household in addition to purely economic ones. The animals added to family security by providing meat, and sometimes milk, and were used as savings for retirement, hard times, or special expenses (Eastman and Gray 1987:39-50).

The livestock also served important social and cultural functions. Small-scale producers stressed the importance of the quality of life that ranching provided them and their families. They spoke of preserving a working relationship with the land that could be passed with pride to their children. Owning animals was a way for them to reaffirm ancestral ties to lands and heritage. Often, owning animals allowed the family to stay in the ancestral, rural community, and to continue part of a traditional lifestyle (Eastman and Gray 1987:39-50).

The Española/Canjilon study will gather information on these economic, social, and cultural contributions at a time of demographic change in the region. Following the format of earlier research (Eastman and others 1971, Eastman and others 1979, Gray 1974), the study will be organized around a written questionnaire, supplemented by personal interviews. The questions will be grouped to elicit the following information:

- a. Background information on the permittee and his/her family.
- b. Background information on the livestock operation.
- c. Contribution of the livestock operation to the household economy.
- d. Contribution of the livestock operation to the cultural, lifestyle, and land-use values of the family.
- e. Contribution of the livestock operation to the family's participation in the social network of the community.
- f. Other contributions of the livestock operation considered important by the permittee.

Respondents will have an opportunity to discuss sustainable resource use, land loss issues, and operating under a federal grazing permit in an interview after discussion of the questionnaire. Information from this study will be compared to information from earlier studies to assess possible changes in the role of livestock operations between the time periods. The working hypothesis is that there are no significant differences between the current contributions of livestock and those in the earlier studies.

Research Significance _____

This research will contribute significantly toward understanding the role and dynamics of grazing operations on public lands. The project will also have strong implications for National Forest land management in northern New Mexico and in other areas with culturally diverse user groups. Questions of land use and grazing management are critical political issues in the region, as is continued federal

ownership of public lands. Political leaders and land managers at the local, regional, and national levels require this type of information to make informed resource-use decisions and policies. Land managers from state and federal agencies require knowledge of the results and difficulties inherent in implementing grazing and resource-use policies. Other social scientists and ecologists will also find this work useful, especially those examining the results of intercultural resource conflict and the overall role of human culture as a critical factor in regional ecology. Most importantly, the people of northern New Mexico should benefit because the public and federal agencies will gain a better understanding of their culture and the role that livestock operations play in maintaining cultural traditions and livelihood.

References

- Briggs, Charles L.; Van Ness, John R. 1987. Introduction. In: Briggs, Charles L.; Van Ness, John R., eds. *Land, water, and culture: new perspectives on Hispanic land grants*. Albuquerque, NM: University of New Mexico Press: 6-12.
- de Buys, William. 1985. *Enchantment and exploitation: the life and hard times of a New Mexico mountain range*. Albuquerque, NM: University of New Mexico Press.
- Earls, Amy Clair. 1985. *The organization of Piro Pueblo subsistence: A.D. 1300 to 1680*. Albuquerque, NM: University of New Mexico. Ph.D. dissertation.
- Eastman, Clyde; Carruthers, Garrey; Liefer, James A. 1971. *Evaluation of attitudes toward land in north-central New Mexico*. Las Cruces, NM: New Mexico State University. Agricultural Experiment Station Bulletin 577.
- Eastman, Clyde; Gray, James R. 1987. *Community grazing: practice and potential in New Mexico*. Albuquerque, NM: University of New Mexico Press.
- Eastman, Clyde; Harper, Wilmer; Guerra, Juan Carlos; Gomez, Bealquin. 1979. *New Mexico small farms: a socioeconomic profile*. Las Cruces, NM: New Mexico State University. Agricultural Experiment Station Bulletin 407.
- Fowler, J.M.; Rush, D.; Hawkes, J.M.; Darden, T.D. 1994. *Economic characteristics of the western livestock industry*. Las Cruces, NM: New Mexico State University. Range Improvement Task Force, Agricultural Experiment Station, Cooperative Extension Service, College of Agriculture and Home Economics Report 35.
- Gray, James R. 1974. *Economic benefits from small livestock ranches in north-central New Mexico*. Las Cruces, NM: New Mexico State University. Agricultural Experiment Station Bulletin 280.
- Harper, Allan G.; Cordova, Andrew R.; Oberg, Kalervo. 1943. *Man and resources in the middle Rio Grande valley*. Albuquerque, NM: University of New Mexico Press.
- Hassell, M. J. 1968. *The people of northern New Mexico and the national forests*. Albuquerque, NM: USDA Forest Service. Southwestern Region. Manuscript on file.
- Hassell, M. J. 1981. *Northern New Mexico policy review and action plan*. Albuquerque, NM: USDA Forest Service. Southwestern Region. Memo on file.
- Hurst, William D. 1972. *Region 3 policy on managing national forest land in northern New Mexico*. Albuquerque, NM: USDA Forest Service. Southwestern Region. Memo on file.
- Korte, Tim. 1996. *Tradition vs. environmentalists: fight flares over wood gathering*. The Press Democrat (Santa Rosa, California). January 13.
- McClellan, Doug. 1995. *Protesters hang environmentalists in effigy: rival rally takes issue with message*. Albuquerque Journal. November 25.
- Ragan, Tom. 1996. *Forest feuds eyed in blast: FBI probes Española bombing*. Albuquerque Journal. January 9.
- Rothman, Hal. 1989. *Cultural and environmental change on the Pajarito Plateau*. New Mexico Historical Review 64(2): 185-211.
- Simmons, Marc. 1979. *History of Pueblo-Spanish relations to 1821*. In: Ortiz, Alfonso, ed. *Handbook of North American Indians: Southwest (9)*. Washington, DC: Smithsonian Institution: 178-193.
- Van Ness, John R. 1987. *Hispanic land grants: ecology and subsistence in the uplands of northern New Mexico and southern Colorado*. In: Briggs, Charles L.; Van Ness, John R., eds. *Land, water, and culture: new perspectives on Hispanic land grants*. Albuquerque, NM: University of New Mexico Press: 141-214.
- Wozniak, Frank E. 1995. *Human ecology and ethnology*. In: Finch, Deborah M.; Tainter, Joseph A., eds. *Ecology, diversity, and sustainability of the middle Rio Grande basin*. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-GTR-268: 29-51.

“Southwest Strategy” Update

Steve Kluge

Abstract—The Southwest Strategy is an effort by federal agencies to work with each other, the public, and tribal, state, and local agencies to maintain and restore the cultural, economic, and environmental quality of life in Arizona and New Mexico. This update explains the strategy and its progress to date.

On December 16, 1997, nine federal agencies in Arizona and New Mexico committed to working with the public and each other in a collaborative effort which is now known as the “Southwest Strategy.” This is a bulletin to share information with employees about what has happened since that date. If your questions are not answered, please see the last section of this update for contacts.

What is the Southwest Strategy? _____

The Southwest Strategy is a commitment by federal agencies involved in natural resources management to work in collaboration with each other, the public, and tribal, state, and local governments. The federal agencies participating in the Southwest Strategy recognize and respect the jurisdictional authority of the Governors and sovereign nations of Arizona and New Mexico. The goal of the strategy is to maintain and restore the cultural, economic, and environmental quality of life in Arizona and New Mexico. The strategy will address community development and natural resources conservation and management within the jurisdictions of the involved federal agencies. It will proceed in a manner that is scientifically based, legally defensible, and implementable.

Which Federal Agencies are Involved? _____

Many agencies within the Departments of Agriculture, Defense and the Interior are currently participating in the Southwest Strategy. Agencies included to date are the Bureau of Land Management, U.S. Geological Survey, Fish and Wildlife Service, Bureau of Indian Affairs, National Park

Service, Bureau of Reclamation, Natural Resources Conservation Service, Forest Service, Environmental Protection Agency and the Department of Defense. Other departments or agencies may join later.

Why Do This? _____

Management of federal lands has become increasingly complex in recent years. Arizona and New Mexico have large expanses of public and tribal lands intermingled with private lands, fast growing metropolitan centers, scarce water resources, unique cultural resources, diverse and fragile ecosystems with numerous endangered species, and many competing demands on public lands and water resources. Agencies, tribes, and the public need to work better together in a comprehensive, rather than piecemeal, effort.

How Will This Be Done? _____

A collaborative problem solving approach will be used to address natural resources issues. Collaboration is a process through which parties who see different aspects of a problem can constructively explore their differences and search for solutions. Through this approach concerns are heard and addressed, information is shared, and technical knowledge sought out.

Collaboration is not an end in and of itself, but is a means to achieve more consistent and responsive service to the public. It is also an agreement to continue talking despite differences and changing circumstances.

Will This Strategy Affect Ongoing Agency Business? _____

No and yes. Agency work will continue as collaborative processes are being developed. The legal and regulatory responsibilities for each agency will remain the framework for agency work, as always.

However, this is a new way of doing business. We want to learn from and build upon existing successes as we deal with increasingly complex issues in Arizona and New Mexico.

What is Happening? _____

During the first stage of the strategy, federal agencies have greatly improved interagency communication and collaboration. A number of internal interagency teams are addressing issues of immediate concern to federal agencies in the Southwest, such as community development, Endangered Species Act Section 7 streamlining, legal issues, and communications.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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In the second stage, the public and the federal agencies will jointly design processes for future collaboration. State, tribal and local governments, nongovernmental organizations, the private sector, and interested individuals will be encouraged to participate. A few contacts have already been made as interested groups have sought information about the Southwest Strategy, such as Arizona's and New Mexico's Soil and Water Conservation Districts and the Arizona Resource Advisory Council.

In the third stage, the participants will use the new processes to develop a comprehensive strategy to manage natural resources in a manner that maintains and restores the cultural, economic and environmental quality of life in the Southwest.

Two small Southwest Strategy offices are being established in Albuquerque and Phoenix. There will be two individuals working in Albuquerque and one in Phoenix. These offices will coordinate activities, collect and disseminate work products, and act as points of contact for both the public and agency personnel. The Albuquerque Southwest Strategy Office will be up and running in mid-May and the Phoenix office sometime later this summer.

How Will Non-Federal Partners Participate?

In May 1997, initial meetings were held with representatives of organizations, state and local governments, and individual citizens. Meetings will also be held with tribal leaders. These meetings seek input on ways to launch future collaborative efforts that will ultimately define the comprehensive strategy for resolving complex natural resource issues while still recognizing and respecting federal Governors', tribal and local authority.

How Are the Federal Agencies Organized Today to Proceed with the Southwest Strategy?

The Regional Executive Committee is comprised of Southwest regional agency heads. The Regional Executive Committee is co-chaired by the U.S. Forest Service's Regional Forester and U.S. Fish and Wildlife Service's Regional Director. The Department of Defense Environmental Coordinator participates for the Department of Defense. The Regional Executive Committee meets at least once a month.

The Regional Implementation Team serves as staff to the Regional Executive Committee. Each participating agency has a representative on the Regional Implementation Team.

The national executives and their staffs provide support, guidance and oversight to the regional executives and their staff. The national executive co-leads are the Director of the Fish and Wildlife Service and the Chief of the USDA-Forest Service. The national executives and their staff bring a broad perspective to the issues in the Southwest. The national executives will also resolve issues elevated by the Regional Executive Committee.

In the first stage of the Strategy, federal work groups were established with representatives from the field, regional, and national staffs. The roles of the work groups vary. Some were designed to help get the strategy started. Others were charged with developing ways to solve critical, immediate issues. Immediate issues are those that involve species of animals or plants or resources or the public at immediate risk, or those issues that involve litigation.

Some of the groups will only have a short-term life span while others may be ongoing. The Regional Implementation Team provides guidance and direction to these groups.

What Work Groups Have Been Organized to Date?

The Communications/Collaboration Design Work Group is comprised of two teams. The Communications Team (COM) develops and releases information about the Southwest Strategy to both federal employees and the public. The Collaboration Design Team (CDT) will assist agencies, tribes and the public in developing processes for collaboration.

The Information Resource Management Work Group will identify ways for participants to share information and provide information in usable formats.

The Research and Data Collection Work Group will identify and respond to scientific data gaps and research needs.

The Section 7 Streamlining Work Group is developing ways to make the Section 7 consultation process under the Endangered Species Act more efficient.

The Legal Work Group provides technical and legal support, and coordination of litigation issues.

The Water Resources Work Group will collaborate with federal, tribal, state and local authorities to design an interagency process to address Clean Water Act compliance and the Clean Water Action Plan.

The Community Development Work Group identifies ways to address the economic and social effects on communities resulting from grazing management changes and other natural resource decisions.

The Endangered Species Act Work Group will coordinate the implementation of requirements found in Biological Opinions, as well as recovery activities among federal agencies.

How is This Funded?

Funding to develop this strategy is coming from within existing agency budgets.

How Long Will it Take to Develop the Southwest Strategy?

Developing collaboration processes with the public is starting. This will proceed at different paces in different areas and will take at least several months to evolve. Some contacts have already been made. The agencies are encouraged by the number of individuals and groups who have asked to participate.

How do I Obtain Further Information?

Questions regarding this interagency strategy may be addressed to the Directors of Public Affairs for the Southwestern Region of the Forest Service in Albuquerque, Carolyn Bye, 505/842-3290, or the U.S. Fish and Wildlife Service in Albuquerque, Tom Bauer, 505/248-6911.

In addition to these interagency spokespersons, each agency has designated a contact point within their offices located within the Southwest. These contact persons will handle internal and external requests for information:

Department of the Interior

Bureau of Land Management:

Kitty Mulkey (NM)	505/438-7514
Deborah Stevens (AZ)	602/417-9215

Bureau of Indian Affairs:

John Philbin (AZ)	602/379-6798
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National Park Service:

Cecilia Matic	505/988-6014
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Geological Survey:

Pat Jorgenson	650/329-4011
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Bureau of Reclamation:

Vicki Fox (NM)	505/248-5371
Bob Walsh (AZ)	702/293-8421

Fish and Wildlife Service:

Tom Bauer	505/248-6911
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Department of Agriculture

Forest Service:

Carolyn A Bye	505/842-3290
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Natural Resources Conservation Service:

Gerry Gonzalez (AZ)	602/280-8777
Rebecca de la Torre (NM)	505/761-4404

Department of Defense

Region VI (NM):

Thomas Rennie	214/767-4678
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Region IX (AZ)

Cindi Flemming	619/532-2297
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Rio Grande/Rio Bravo Basin Coalition

Sarah Kotchian

In June 1994, one hundred people gathered for the first Uniting the Basin Conference in El Paso to discuss the state of their basin and to explore ways to improve its sustainability for future generations. One of the recommendations of that conference was the formation of an international non-governmental coalition of groups throughout the Basin to share information and ideas and facilitate local efforts to improve the river and the quality of life along it for all members of the ecosystem. In 1995, a steering committee met to begin to make that recommendation a reality. The non-profit Coalition now has a 15-member board of directors from throughout the basin, and partners and friends representing a wide variety of grassroots environmental and business groups.

The response to Coalition initiatives has been tremendous, indicating the need and support for a Basin-wide network. Within the first three years, the Coalition has raised money for and donated computers and financial resources to river groups throughout the Basin, providing internet access and communication linkages between groups and sub-Basin areas facing similar issues. The Coalition also functions as an information clearinghouse, providing a web page (www.utep.edu/rioweb/) and BasinNet listserve, and publishing a newsletter called "La Corriente". It has founded the enormously successful Dia Del Rio, a celebration and restoration of the river on the third Saturday of October each year by communities all up and down the river. The Dia Del Rio celebration in turn inspired the Gathering of Waters project initiated by artist Basia Irland, an initiative which collects river water in a vessel and has been transferring it community to community, uniting upstream and downstream partners. The Coalition has sponsored

fundraising trainings in both Mexico and the U.S., to strengthen the capacity of local groups to be effective in river protection. And it co-sponsored the first River Stewardship conference with the New Mexico Conferences of Churches and the U.S. Catholic Bishops this past spring to empower local communities of faith to become more active on river sustainability issues. In September, 1998, the Coalition is hosting the Uniting the Basin Congress in El Paso, Texas. The Coalition has two staff members, Bess Metcalf, the Executive Director, and Gabriela Vale, the Mexican Outreach Coordinator for supporting Mexican grassroots river groups.

The Coalition is dedicated to the sustainability of the ecology, economy, and cultures of the Rio Grande/Rio Bravo Basin through international cooperation and communication, education and public awareness, and positive action. It has adopted principles that include strengthening grassroots groups of citizen throughout the river basin, empowerment of local communities to determine their own issues and find their own solutions, a commitment to representing the social, cultural, geographic, and ethnic diversity of the Basin, and dedication to dialogue, consensus-building, and the democratic process.

For more information on the Coalition, contact:
Bess Metcalf, Executive Director,
Rio Grande/Rio Bravo Basin Coalition
c/o C.E.R.M., P.O. Box 645, Burges Hall Room 315,
El Paso, TX 79908
(915) 747-5720
email: bmetcalf@utep.edu

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Sarah Kotchian is the Co-Chair, Rio Grande/Rio Bravo Basin Coalition.

River and Riparian Issues



Watershed/River Channel Linkages: the Upper Rio Grande Basin and the Middle Rio Grande Bosque

Jeffrey C. Whitney

Abstract—There continues to be a great deal of interest and discussion surrounding the demands of water management and allocation and the relationship to ecological integrity of the Rio Grande riparian ecosystem. Current river management too often fails to consider the importance of natural variability of flows. What is consistently overlooked is the relationship of a stream course to its forming watershed. The standard practice of managing for one or more of a few important or imperiled species by defining how little water can be left in the river is not adequate based upon new scientific understanding. Adaptive management approaches can be used to manage for whole river ecosystems concurrent with providing societal and cultural demands on these natural systems.

The Middle Rio Grande (MRG) riparian forest, or “bosque”, represents the largest cottonwood gallery riparian forest in the southwestern United States. This reach of the Rio Grande extends from Cochiti dam downstream 260 km to San Marcial, New Mexico. It constitutes 8 percent of the river’s total length and 34 percent of its length in New Mexico. The current bosque is a relict of past management activities and is notably different than its historic character. The physical and biological characteristics of southwestern riparian systems are complex. Natural processes in southwestern riparian systems and the ecological adaptations of vegetation affected by flood induced disturbance are fundamental aspects to be considered.

What is consistently overlooked is the relationship of a stream course to its forming watershed. Once understood, this relationship facilitates the ability to recognize the character and condition of the riparian reach under study both from a temporal and spatial perspective. The annual natural variability of flows from a watershed and infrequent episodic high flows (floods) are important aspects in understanding the expected and necessary natural variability of flows. Flood events reset the condition of these systems. Too often the casual observer interprets the effects of reforming floods as “destructive.” While understandable, this conclusion may be hasty and is often incorrect.

A complex set of factors are involved in the development and maintenance of these landscapes. The variability in

hydrology and river morphology of these systems precludes use of random sampling in order to accurately characterize these dynamic habitats. As a result of man’s activity in most southwestern watersheds today, the changes to the hydrology and the loss of active floodplain combined with changes in sediment supply and availability in the river system have all contributed to a loss of biological integrity.

The benefits of inter-annual flooding is a potential resource that was effectively used by the original floodplain system. Development within the floodplain, accompanied by diking, alterations of the natural hydrograph, and channelizing, are the results of the perception that flooding must be controlled.

Gregory and others (1991) describe riparian zones, the interfaces between terrestrial and aquatic ecosystems, as a mosaic of land forms, communities, and environments within the larger landscape. These were perhaps the first authors to present an ecosystem perspective of riparian zones that focuses on the ecological linkages between terrestrial and aquatic ecosystems within the context of fluvial land forms and the geomorphic processes that create them. They observed “that geomorphic processes create a mosaic of stream channels and floodplain within the valley floor. Geomorphic characteristics and other processes including stochastic disturbance both upland and fluvial in origin affect riparian zones, determining the spatial pattern and successional development of riparian vegetation.”

In general, the factors affecting the development of southwestern riparian habitat are as follows:

1. Creation of a favorable seedbed;
2. Progression of tree stands from nursery bars to senescent individuals as they continually modify their own habitat;
3. Light to moderate flooding favors the establishment and development through deposition of nutrient-rich sediments and increased soil moisture; and
4. Successful seeding cannot be expected on an annual basis since it depends upon a “proper sequence of flooding,” that is, no flooding large enough to be catastrophic until stands are well developed.

Stromberg (1993) found that flow volume and the related attributes of water-table recharge and floodplain soil wetting are primary factors regulating riparian vegetation abundance. For example, many riparian tree species in the arid southwest are evolutionarily adapted to germinate after high spring flows, which occur as a result of snowmelt and run-off from winter rains, whereas others germinate after high summer flows, which are driven by monsoonal summer rains (Stromberg and others 1991). Many arid land streams are water limited on an annual or seasonal basis

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because discharge has such a high degree of temporal flux (Graf 1982; Poff and Ward 1989). The combination of high peak flows in conjunction with low mean annual flows may serve to reduce the vegetation of small streams (Stromberg and Patten 1990). Flooding plays an important role in regulating accumulations of woody debris and nutrient dynamics in southwestern riparian ecosystems. In arid landscapes where precipitation is limited, moisture made available through fluvial interactions may play an essential role in facilitating the release of nutrients contained within wood and leaf litter on the forest floor (Ellis and others 1995). Flood flows in some systems play a major part in 'shaping' valley floors and in physically delimiting floodplain from adjacent uplands, by variously scouring or depositing alluvial sediment (Gregory and others 1991; Hill and others 1991). Larger streams thus might be expected to have a greater extent of sites suitable for establishing riparian vegetation.

Flood flows of a given magnitude, frequency, and seasonal timing are also important because of their roles in influencing species diversity patterns and in creating opportunities for riparian vegetation recruitment.

Beyond the physical characteristics of watersheds and their resultant channels, supplies of minerals and detritus (nutrients) is consideration of the supply and availability of elements to the stream biota is important. The impact of short-term events like storms on the elemental dynamics in streams should be assessed and compared with other controls. These factors are essential for rates of primary productivity and decomposition in streams. The major controls on element supply to a stream include watershed geology and hydrology, soil processes, land-use practices, landscape vegetation, and atmospheric loading. These watershed- or landscape-level process define the overall supply of elements to a stream. (J.L.Meyer and others 1988).

Landscape Scale Ecosystem Management

The study of spatial and temporal patterns across landscapes is central to formulating ecosystem management principles. The hierarchical structure of ecological systems allow the characterization of ecosystems and the identification of patterns and processes at different scales. Ecosystem composition, structure, and function determine diversity patterns across a range of spatial-temporal scales. There is no single correct scale at which to study and manage ecological patterns, processes, and diversity. The ecological hierarchy of interest is determined by the purpose of each project. Hierarchical monitoring schemes must be formulated that consider all scales of ecological organization. Patterns of natural variability across a range of scales must be defined if ecosystems are to be sustained at all relevant scales. Landscapes are heterogeneous mosaics of patches (Forman and Godron 1986; Urban and others 1987).

Programmatic riparian restoration is further complicated since rainfall and streamflow do not annually coincide with seed drop from many pioneer riparian tree species. Many arid land streams are water-limited on an annual or seasonal basis because discharge has such a high degree of temporal flux (Graf 1982; Poff and Ward 1989). The

combination of re-organizing high peak flows in conjunction with low mean annual flows may serve to reduce the vegetative cover of (small) streams (Stromberg 1993).

An alternative hypothesis is that geomorphological features rather than hydrological features regulate riparian abundance within a watershed. As stream flow increases, so too does the magnitude of the low frequency hydrological events. Flood flows in some systems play a major part in shaping valley floors and in physically delimiting floodplains from adjacent uplands, by variously scouring or depositing alluvial sediment (Gregory and others 1991; Hill and others 1991). Larger streams thus might be expected to have a greater aerial extent of sites suitable for the establishment of riparian vegetation.

Flood flows of a given magnitude, frequency and seasonal timing are also important because of their roles in influencing species diversity patterns and in creating opportunities for riparian recruitment.

Linkages Between Watershed Condition and Flows

There is an obvious direct relationship between watersheds and the water courses which result. As conditions within a watershed are altered either by natural biotic (for example insect mortality to large stands of forested trees) or abiotic events (such as fire, landslides) or by anthropogenic activities, development, road construction, timber harvesting or livestock grazing as examples, the associated watercourses adjust to the changes in discharge, seasonality, or landform. There is little argument that anthropogenic activities in riparian systems and their associated watersheds have a marked negative impact upon these natural systems. The magnitude and frequency of these activities as well as the timing of the particular action have a significant role in the exhibited resulting effects. To a large extent mitigation and management can reduce these negative impacts to tolerable levels and riparian system functions may remain within the limits of acceptable natural variation.

A properly functioning riparian stream system (including the associated watershed) can be referred to as being in dynamic equilibrium. This can also be thought of as being within the acceptable limits of natural variation for that stream system. In all discussions regarding river morphology, it is important to recognize the differences within spatial and temporal scales. To describe a river system as being in a state of dynamic equilibrium (or energy balance) does not mean that it is static. To the contrary, this "equilibrium results from a collection of processes that are by definition predicated on change" through time (Crawford and others 1993). For example, even during periods when the entire river system is considered to be in a state of dynamic equilibrium, changes constantly occur in channel segments or reaches as small as the outside bend of a meander, or as large as many river kilometers upstream, and downstream from a tributary inflow (Whitney 1996). Likewise, this state of dynamic equilibrium, can accommodate climatic deviations from the norm distinguished between natural and human-caused perturbations. The geomorphic process triggered in response to a change in

magnitude or duration of a variable, regardless of the cause, will be the same (Leopold and others 1964). The river constantly adjusts, always trying to establish a new equilibrium between its discharge and sediment load (Bullard and Wells 1992).

Often times when specialists go to the river to assess what needs to be done to restore the site, the focus remains on the condition of the channel and aquatic habitat alone without consideration of upstream factors responsible for the current condition of the reach being addressed.

Beyond that, many have difficulty imagining, let alone measuring, highly variable conditions over complex large watersheds. Because the effects of changes within watersheds are multifaceted and difficult to predict, planning and implementation of successful active restoration projects must include monitoring key watershed processes. Aspects to be monitored include geomorphic conditions, relative topographic relief, soils, climate, permeability, vegetative ground cover, water chemistry, nutrient production, movement and cycling, flow characteristics, sediment delivery and transport regimes, riparian conditions, and aquatic organisms.

Natural Variability in River Flows

Natural river systems can and should be allowed to repair and maintain themselves (Poff and others 1997). Restoring riparian ecosystems must involve restoring or at least mimicking their natural flow regime. Realistically this will involve a mix of human-aided and natural recovery methods. Management of a healthy river is more than creating an artificial constant low flow or tolerating the occasional "100-year flood" be it natural or orchestrated by man. There are five often overlooked components of a river's flow regime: magnitude, frequency, duration, timing and rate of change. Flow modification has cascading effects on the ecological integrity of rivers. The importance of natural variability to aquatic and riparian ecosystems demonstrate that unfettered rivers have multiple benefits for nature and for human society. Changes to the natural flow regime constitute one particularly important and underappreciated cause of declining health of rivers. Natural variability characterizes all ecosystems. Variability in river flow is a prime example of such natural variability. Each river has a natural flow regime, which can be altered by a variety of human actions including dams, diversions and diverse ways in which hydrologic pathways are altered. Natural variability in river flow creates a wide range of habitat types and ecosystem processes that maintain the natural biological diversity of aquatic and riparian (stream side) species. A major consequence of this natural variability is that all species experience favorable conditions at some time, preventing any one species from dominating.

Alterations of the natural flow regime result in numerous physical, chemical and biological changes to river ecosystems and may traverse many political boundaries. (Tyus 1990).

Changes in flow shape and duration can have direct and indirect effects. Direct effects of flow alterations are certainly important if migrations are blocked, fish are trapped

in de-watered sections, or reproduction is disrupted. Insidious effects may be far more detrimental, and include alterations and loss of stream habitat, introduction of competing non-native fishes, degradation of water quality, and other effects. For example with a reduction in steam flooding change nutrient cycles and disrupt food webs which have serious ecosystem consequences.

Examples include not just fish migrations but also recruitment of riparian trees, maintenance of sandbars in river channels, and sustenance of wetland habitat dependent upon flood plain inundation. Our understanding of the linkages between natural flow regime and the ecological functioning of rivers provides a powerful scientific basis for river management and restoration.

Water resource developments and operations may affect stream resources both beneficially and adversely (Tyus 1990). Return flows from irrigation projects maybe warmer, sediment laden, and contaminated with chemicals, including biocides and fertilizers. Conversely return flows into river channels during droughts can provide some beneficial effects. Planned flows can mitigate and potentially enhance natural components of riverine systems.

Instream flows are a public trust, and stream ecosystems must be protected as irreplaceable resources. Letting a river do its own thing—come drought or high water—is more complicated. Most western states have recognized in-stream flow of some form. This may be by design or by default depending upon the river system being examined. In fact, all 11 western states have some degree of in stream flow mechanisms. Despite the lack of an existing instream flow designation in New Mexico at this time, the State Attorney General and The Office of the State Engineer in April of 1998 announced that in-stream flow does have value for fish, wildlife, and ecological purposes. With the caveat that this would only be possible if an existing water right was employed for such purposes, it still is a positive move toward a fuller appreciation for free flowing water in riverine systems in New Mexico.

Natural Flood Flow Disturbance

The variability of watershed condition, channel morphology, flow regimes, differences in flood generated disturbances, and the intensity of those perturbations are all factors which have a direct role in the location, establishment, and relative maturity of a particular stand of riparian broadleaf trees.

Hypotheses on the coexistence of plant species (Connell 1979), niche differentiation (Grubb 1977), and resource partitioning (Denslow 1980) in plant communities have relied heavily on the requirement for some form of disturbance during the life cycles of many plant species. In general, disturbance reduces the dominance of a site by established individuals and creates openings for colonization and growth by new individuals. Establishment of woody plants species associated with riverine systems in the arid southwest are no exception to these general principles.

Large volume floods are the primary disturbance event affecting southwestern riparian systems (Stromberg and others 1991). Typically, these large flood events occur on approximately a 10 year recurrence frequency (House 1993).

In uncontrolled systems, estimating flood frequency is complicated because climate affects the magnitude and frequency of storms that cause floods (Webb and Betancourt 1992). The magnitude of these recurring flood events is dependent upon several features including storm event, watershed condition (LaFayette and DeBano 1990), soil saturation including snowmelt potential (House 1993), channel morphology, and condition and associated riparian vegetation cover (Stromberg and others 1991).

Desert streams draining large watersheds provide an excellent opportunity to test successional concepts in running waters (Fisher 1986). The importance of hydrology to arid land riparian vegetation has long been recognized. Zimmerman (1969) stated that: "Drainage area, geology, and flow regimen are probably the three most important controls in the distribution of valley-floor vegetation" in the arid southwest. Unfortunately, all too often researchers and field personnel of various land management agencies have focused too intently upon the FORM of a given riparian area and not given substantive consideration to the FUNCTION of the area evaluated (LaFayette and DeBano 1990).

In a generalized sense, little of what we know about lotic systems has come from work done on southwestern "desert" streams. Fisher and Minckley (1978) found that the generalized xero-riparian stream is "hydrologically flashy," responding rapidly to summer storm events with "wall of water" flash floods up to 50 cubic meters per second. The product of this and other general features of desert streams yields a stream where the main channel is wide, shaped largely by rare flooding events.

A principle effect of natural disturbance is to alter the availability of resources for plant growth. Pickett and White (1985) suggested that there are at least two mechanisms by which disturbances can temporarily increase the availability of light, water, and soil nutrients. The first is simply the reduction in rates of uptake or use of resources due to the loss of biomass. The second mechanism is the decomposition and mineralization of nutrients held in organic matter (Bormann and Likens 1979). Large scale disturbance as a result of out-of-bank or scouring flood flows produces a temporary increase in some of the resources necessary for the establishment of new stands of canopy species and understory plants in riparian systems in the arid southwest. In addition, there is also a net gain of energy into these systems through the movement of nutrients into the riparian zone from adjacent uplands (Meyer and others 1988).

There is a positive relationship between disturbance size or intensity and the availability of resources for plant growth. In addition to the expected benefits of reduced biomass per unit area, the degree of reduction in rates of transpiration and interception of water, and the uptake of nutrients, there is typically a high degree of nutrient movement associated with flows of all magnitudes in riparian zones.

An important feature of any increase in resource availability produced by a disturbance is its transient nature. As biomass is re-established at a site, the relative availability of resources for future colonists will, in general, decline. Flood disturbance produces a distinct and marked transient pulse of nutrients and organic matter into the riverine system. This represents a distinctly different pattern to which plant species can respond than that of an intact community which has equilibrated with the rate of supply of

resources (Tilman 1982). In communities where there is rapid regrowth of vegetation following a disturbance, the availability of resources for colonization should reach a peak soon after a disturbance. Consequently, the first plants that become established after a disturbance should benefit from greater availability of resources than plants that become established later. Seedlings of many species of woody plants often establish rapidly. Rapid germination following a disturbance flow should be particularly critical for species of woody plants that are intolerant of shade.

Patterns of seed production and dispersal vary widely among woody plants. One of the most conspicuous patterns of seed production and dispersal is the copious production of light, wind dispersed seed in the spring coinciding with typical spring runoff peaks. This reproductive strategy is generally correlated with the ability to respond to large disturbances (Baker 1974). This is the case for many "pioneer" tree and shrub species which occupy recently disturbed, scoured, or deposited sediments in and along the channels of southwestern riparian systems.

There is a high degree of variability among riparian tree species to distinct geomorphological and hydrological stream habitats (Asplund 1988). Brady and others (1985) described the development of riparian gallery forest as beginning with moist nursery bars located in overflow channels or abandoned meanders that provide moist areas for seepwillow (*Baccharis glutinosa*) to pioneer. As the stand of seepwillow develops, sediment aggradation occurs providing a seed bed for cottonwood (*Populus fremontii*) seeds, or the expansion of Gooding willow (*Salix goodingii*) roots.

The high degree of variation in stand structure and composition along a given reach in desert riparian systems is an expression of a number of variables. These include but are not limited to: flow regime, substrate, elevation, seed source, timing of seed dispersal, anthropogenic activities. Therefore, it is important to take the long-term landscape (spatio-temporal) view of these systems if we are to truly understand the complex interactions of the factors contributing to the functioning of the channel and the degree to which vegetation is expressed. In addition, the associated riparian vegetation is found along the periphery of the flood channel. The broad shallow base flows meander over the sandy alluvium often is some distance away from the riparian vegetation. Where sediments are deep, flows of low discharge may occur only below the sediment surface. In these situations, surface flow only emerges where associated with underlying shallow bedrock and percolation occurs where bedrock recedes. This intermittency is a function of channel morphology and discharge. This leads to differential expression of the associated riparian communities found along the edge of the channel at bankfull flow. When sufficiently large changes between erosion and depositional processes occur, the riparian area may be unable to adjust to change, loses its equilibrium, and in extreme cases may be permanently altered and possibly damaged (LaFayette and DeBano 1990).

These disturbance events remove most of the stream biota excluding native fishes, and bank vegetation. The magnitude of the flow determines the degree of regeneration and recruitment of the primary flora. Conversely, in the absence of such flows, the existing stand can become either senescent or can be overtaken by such species as salt cedar (*Tamarix pentandra*). Thus, one view of succession is of a temporal

nature looking at conditions at intervals reset by flows of varying magnitude and frequency. In contrast, many authors have attempted to explain these systems using a Clementsian climax succession paradigm. This concept has received considerable attention and many current classification systems strive to make these riparian habitats fit some climax succession schedule. However, this has been difficult to describe adequately and impossible to predict in these disturbance driven systems. Fisher and Minckley (1978) concluded that "an ecosystem in which the entire species pool consists of 'pioneer' species is unlikely to exhibit temporal succession." The community and how the primary species are classified thus may make application of a Clementsian model awkward if not inappropriate. Sampling and extrapolating that data to fit the balance of the study area is misleading and ineffective in describing a riparian community overall due to variability of geology, valley form and substrate. It may well be that the appropriate means to measure these sites is to evaluate the species richness and the degree of maturity or size class diversity in the particular stand over time between significant disturbance flows.

Biological Integrity

The most influential definition of biological integrity was proposed by Frey (1975) and further described by Karr and Dudley 1981. The concept is defined as "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat of the region" (Karr 1991).

Angermeier and Karr (1994) identified two important distinctions between integrity and diversity from this definition. First, system integrity is reflected in both the biotic elements and the processes that generate and maintain those elements, whereas diversity describes only the elements. Integrity depends on processes occurring over many spatiotemporal scales, including cellular processes giving rise to genetic elements and ecosystem processes regulating the flow of energy and materials. The second distinction between integrity and diversity is that only integrity is directly associated with evolutionary context.

When a river is dammed, integrity is reduced, resulting in population declines which are adapted to the natural hydrological regime. Integrity goals also provide for natural fluctuation in element composition. Loss of a particular element, a particular species for example, or replacement by a regionally appropriate one need not indicate a loss of integrity unless the processes associated with the element's maintenance become impaired. Biological integrity is thus generally defined as a system's ability to generate and maintain adaptive biotic elements through natural evolutionary processes. Current loss of biological integrity includes loss of diversity and breakdown in the processes necessary to generate future diversity.

Ecological Restoration

The goal of ecological restoration is to produce a self-sustaining system as similar as possible to the native biota.

Restoration goals must be based on social and political constraints as well as biological potential. Restoration methods usually mimic recovery from natural perturbations and reflect important organizational processes. Common approaches for aquatic systems include manipulating water quality, habitat structure, hydrology, riparian/watershed vegetation, and (less frequently) animal populations (Gore 1985; Osborne and others 1993). Restoration of terrestrial systems typically focuses on establishing native vegetation and manipulating succession. To maximize effectiveness, restoration efforts should employ and encourage natural ecological processes rather than technological fixes and should incorporate spatiotemporal scales large enough to maintain the full range of habitats necessary for the biota to persist under the expected disturbance regime. Riparian zones and floodplain are critical landscape components linking aquatic and terrestrial systems; they regulate aquatic habitat formation as well as movement of water, nutrients, and organic material into aquatic habitats (Gregory and others 1991).

"Restoration" may be reasonable in many cases. In other instances, enhancement of the existing altered character of our streams and rivers may be the best we can hope to realize. Most riparian habitats are now a highly controlled or altered system with much of their ecological integrity hampered by our past or continuing activities. The thoughtful application of new understandings to the delicate and intricate balance of nature, recognition of the inevitable range of flood and drought, flexibility in management and legal applications will be necessary for improvement of the riverine habitats. The solution lies in the ability to explore collaboratively means and methods to provide the societal needs while simultaneously sustaining a healthy environment. At the present time there are a number of research, monitoring, and planning activities underway designed to contribute to the overall goal of improvement of southwestern riparian ecosystems. These activities are at all levels of government and many are collaborative efforts.

Policy effectiveness also could be improved by shifting focus from populations and species to landscapes. The organizational processes and ecological contexts that maintain populations typically operate at larger spatiotemporal scales than the populations themselves (Pickett and others 1992). Thus management approaches focusing on strictly aquatic components (for example, designation of a stream reach as wild and scenic or as critical habitat for an imperiled species) are unlikely to be effective over the long-term.

Dr. Hal Salwasser in 1991 made the observation that traditional agricultural, fisheries, forestry, game management, and mining agencies must replace their narrow, commodity and harvest-oriented philosophies with innovative perspectives founded on a broader range of social concerns, longer time frames, and more interagency cooperation. Critical steps toward managing for biological integrity include establishing scientifically defensible benchmarks and assessment criteria. (Angermeier and Karr 1994). Although these steps are potentially contentious, current uses of integrity goals indicate that success is attainable.

The morphic variables that interact to form the dimensions, profile and patterns of modern rivers are often the same variables that have been adversely impacted by development and land use activities. To restore the disturbed

river, the natural stable tendencies must be understood to predict the most probable form. If one works against the natural tendencies of a river course in terms of watershed yield, morphology, and channel and meander geometry. If one works against these tendencies, restoration is generally not successful (Rosgen 1994).

Restoration efforts in the uplands, river corridor, in the floodplain, on public, private and tribal lands is ever increasing. We are instituting Adaptive Management in many arenas to recreate habitat which has been lost or whose quality has been severely affected by our past management activities.

The solution at first blush appears to be either too simplistic or too overwhelming. Clear understanding of what is needed, the operating space for change in administration, and recognizing that we are all part of a basin wide community will provide opportunities to be better stewards of the finite resources we utilize.

Societal Choices

The causes of environmental degradation and loss of biodiversity are rooted in society's values and the ethical foundation from which values are pursued. Solutions are likely to emerge only from a deep-seeded will, not from better technology. Adopting biological integrity as a primary management goal provides a workable framework for sustainable resource use, but fostering integrity requires societal commitment well beyond government regulations and piecemeal protection. Such a commitment includes self-imposed limits of growth and resource consumption, rethinking prevailing views of land stewardship and energy use, and viewing biological conservation as essential rather than as a luxury or nuisance. The decision to conserve or exhaust biotic resources is before us. It can be informed by science and influenced by government policy, but conservation primarily depends on a societal will grounded in recognition of its obligation to the future. (Angermeier and Karr 1994).

Quality of life does reside in a healthy environment. There are numerous economic benefits associated with vibrant, functioning ecosystems. Responsible management and administration at all levels of government and as individuals will be necessary. But without attention to these aspects, significant and perhaps irreversible consequences could result. Ultimately, the habitat we save will be our own.

References

- Angermeier, P. L., and J. R. Karr., 1994. Biological Integrity versus Biological Diversity as Policy Directives: Protecting Biotic Resources. *BioScience* Vol. 44.
- Asplund K., 1988. Reproduction and Geomorphic Adaptations in 4 Species of Riparian Cottonwoods in Central Arizona. Arizona/New Mexico Wildlife Society Joint Meeting. Thatcher, Arizona.
- Baker, H.G., 1974. The evolution of weeds. *Annu. Rev. Ecol. Syst.* 5,1-24.
- Bell, D.T., 1974. Tree stratum composition and distribution in the stream side forest. *American Midland Naturalist.* 92:35-46.
- Bormann, F.H., and G.E. Likens. 1979. "Pattern and Process in a Forested Ecosystem." Springer-Verlag, Berlin and New York.
- Brady, W., D.R. Patton, R. Paxson, and J. Paxson. 1985. The development of Riparian Gallery Forests. In: *Riparian Ecosystems and Their Management; Reconciling Conflicting Uses.* First N. Am. Rip. Conf. USDA F.S., Rocky Mtn. Forest & Range Exp. Station. GTR-RM-120 39-43.
- Bullard, T.F. and S.G. Wells. 1992. Hydrology of the Middle Rio Grande from Velarde to Elephant Butte Reservoir, New Mexico. U.S. Fish and Wildlife Service, Resource Publication 179.
- Connell, J.H., 1979. Tropical rain forests and coral reefs as open non-equilibrium systems. In "Population Dynamics" (Anderson R., B. Turner, and L. Taylor, eds.), pp. 141-163. Blackwell, Oxford.
- Crawford, C.S., A.C. Cully, R. Leutheuser, M.S. Sifuentes, L.H. White, and J.P. Wilbur. 1993 Middle Rio Grande Ecosystem: Bosque Biological Management Plan.
- Denslow, J.S., 1980. Gap partitioning among tropical rainforest trees. *Biotropica* 12, suppl., 47-55.
- Ellis, L.M., J.R. Thibault, M.C. Molles, Jr., and C.S. Crawford. 1995. Effects of Flooding on Woody Debris Biomass and Decomposition in a Southwestern Riparian Forest. In Review: *Canadian Journal of Forest Research.*
- Fisher, Stuart B. 1986. Structure and Dynamics of Desert Streams. In: *Pattern and Processes in Desert Ecosystems*, W.G. Whitford (editor). University of New Mexico Press pp 119-139.
- Fisher, S.G., and W.L. Minckley. 1978 Chemical characteristic of a desert stream in flash flood. *Journal of Arid Environments.* 1:25-33
- Forman, R.T.T. and M. Godron. 1986. Landscape ecology. New York: John Wiley and Sons.
- Frey, D. 1975. Biological integrity of water: an historical perspective. Pages 127-139 in R. K. Ballentine and L. J. Guarraia, eds. *The Integrity of Water.* EPA, Washington DC.
- Gore, J. A., ed. 1985. *The Restoration of Rivers and Streams.* Butterworth, Boston, MA.
- Graf, W.L. 1982. Spatial variation of fluvial processes in semiarid lands, in Thorn, C.E. (ed), "Space and Time in Geomorphology." George Allen & Umvin, New York. 193-277.
- Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An Ecosystem Perspective of Riparian Zones. *BioScience*, 41, 540-550.
- Grubb, P.J., 1977. The maintenance of species-richness in plant communities: the importance of regeneration niche. *Biol. Rev. Cambridge Philos. Soc.* 52, 107-145.
- Hill, M.T., W.S. Platts, and R.L. Beschta. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. *Rivers*, 2, 198-210.
- House, K.P. 1993. The Arizona Floods of January and February 1993. In *Arizona Geology: Vol. 23, No.2, Summer 1993.*
- Karr, J. R. 1991. Biological integrity: a long neglected aspect of water resource management. *Ecological Applications* 1:66-84.
- Karr, J. R., and D. R. Dudley. 1981. Ecological perspective on water quality goals. *Environ. Manage.* 5:55-68.
- Lafayette R.L., and L.F. DeBano. 1990. Watershed Conditions and Riparian Health: Linkages. Watershed Planning and Analysis in Action Symposium Proceedings of IR Conference, Watershed Mgt./IR Divi./American Society Civil Engineers (ASCE). Durango, CO/ July 9-11, 1990 pp 473-484.
- Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Co., San Francisco.
- Levin, S.A. 1992. The problem of pattern and scale in ecology. *Ecology.* 73: 1942-1968.
- Meyer, J.L., W.H. McDowell, T. L. Bott, J.W. Elwood, C. Ishizaki, J. M. Melack, B. L. Peckarsky, B.J. Peterson, and P.A. Rublee. 1988. Elemental dynamics in streams. *J.N.A. Benthol. Soc.* 7(4):410-432.
- Osborne, L. L., P. B. Bayley, and L. W. Higler, eds. 1993. Lowland stream restoration: theory and practice. Special issue. *Freshwater Biol.* 29: 187-342.
- Pickett, S. T. A., V. T. Parker, and P. L. Gieldler. 1992. The new paradigm in ecology: implications for conservation biology above the species level. Pages 65-88 in P. L. Fiedler and S. K. Jain, eds. *Conservation Biology.* Chapman & Hall, New York.
- Pickett, S.T.A., and P.S. White. 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press Inc., New York. 53-68.

- Poff, N.J., and J.V. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure; a regional analysis of streamflow patterns. *Can. J. Fish. Aqua. Sci.*, 46, 1805-Platt, B., Schanta M., Lachowski, H., Maus, P. Landrum, V., and Jan Johnson. 1992. Forest Plan Monitoring: Role of Remote Sensing and GIS on the Mark Twain National Forest. National Workshop-Integrated Ecological and Resource Inventories, Phoenix AZ. WO-WSA-4. April 1992.
- Poff N.J., J. D. Allan, M.B. Bain, J.R. Karr, K. L. Prestegard, B.D. Richter, R. E. Sparks, J. C. Stromberg. 1997. The Natural Flow Regime: A Paradigm for River conservation and Restoration. *BioScience*. June 1997
- Rosgen, D.L., 1994. A classification of natural Rivers. *Catena* 22 pp164-199
- Salwasser, H. 1991. In search of an ecosystem approach to endangered species conservation. Pages 247-265 in K. A. Kohm, ed. *Balancing on the Brink of Extinction*. Island Press, Washington, DC. Schindler, D. W. 1990. Experimental perturbations of whole lakes as tests of hypotheses concerning ecosystem structure and function. *Oikos* 57:25-41.
- Stromberg, J.C., and D.T. Patten. 1990. Riparian vegetation instream flow requirements: a case study from a diverted stream in the eastern Sierra Nevada, California. *Environ. Manage.*, 14,185-194.
- Stromberg, J.C., and D.T. Patten, 1991. Instream flow requirements for cottonwoods at Bishop Creek, Inyo County, California, *Rivers*, Vol. 2, pp 1-11.
- Stromberg, J.C., D.T. Patten, and B.D. Richter. 1991. Flood flows and Dynamics of Sonoran Riparian Forests. *Rivers*, Vol. 2, Num. 3. pp 221-235.
- Stromberg, J.C. 1993. Instream flow models for mixed deciduous riparian vegetation within a semiarid region, *Reg. Riv.: Research & Management*, Vol. 8, 225-235.
- Szaro, R.C. 1989. Riparian and forest and scrubland community types of Arizona and New Mexico. *Desert Plants* 9:70-135.
- Tilman, D. 1982. *Resource Competition and Community Structure*. Princeton Univ. Press, Princeton, New Jersey.
- Tyus, H.M., 1990. Effects of Altered Stream Flows on Fishery Resources. *Fisheries*, vol. 15, No. 3 pp 18-20.
- Urban, D.L; R. V. O'Neill, and H. H. Shugart, Jr. 1987. Landscape ecology: a hierarchical perspective can help scientist understand spatial patterns. *BioScience*. 37: 119-127.
- Urban, D.L., Gardner, R.H., R.V. O'Neill, and S. M. Pearson. 1993. Landscape Ecology-a hierarchical perspective can help scientists understand spatial patterns. *BioScience* 37: 119-127.
- Webb R.H.; J.L. Betancourt. 1992. Climatic Variability and flood Frequency of the Santa Cruz River, Pima County, Arizona. U.S. Geological Survey-Supply Paper 2397, U. S. Govt. Printing Office, Washington D.C.
- Whitney, J.C. 1996. Integration of GIS and Remote Sensing in the Evaluation of Flood Disturbance on the Upper Verde River, Arizona. Masters Thesis, Arizona State University.
- Zimmerman R.L., Plant Ecology of an arid Basin, Tres Alimos-Reddington Area, U.S. Geol. Surv. Prof. Pap. 485-D, U.S. Govt. Printing Office, Washington D.C.

Simulation of Rio Grande Floodplain Inundation Using FLO-2D

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Abstract—Spring floodplain inundation is important to the natural functions of the Rio Grande bosque biological community including cottonwood tree germination and recruitment. To predict floodplain inundation, a two-dimensional flood routing model FLO-2D will be applied to various reaches of the Rio Grande. FLO-2D will assess overbank flooding in terms of the area of inundation, floodplain hydraulics and river discharge timing, frequency and duration. Floodwave attenuation is important in predicting floodplain inundation. Initial FLO-2D applications will be made to the Isleta reach (15 miles) south of Albuquerque and to a 20 mile reach near the Bosque del Apache Wildlife Refuge.

The Rio Grande Bosque Hydrology Group has identified several important projects designed to improve the natural functions of the Rio Grande bosque biological community. One of these projects is to investigate the potential for overbank flooding to support cottonwood tree germination. To predict overbank flooding discharge, the FLO-2D model will be applied to various reaches of the Rio Grande downstream of Cochiti Reservoir. The initial test application of the model was made to a 15 mile reach of the Rio Grande downstream of the Isleta Diversion Dam south of Albuquerque. The second FLO-2D application will be made to a 20 mile river reach near the Bosque del Apache National Wildlife Refuge. FLO-2D will assist in analyzing overbank flooding in terms of timing, frequency and flood duration.

The prediction of overbank flooding and the application of the FLO-2D model is a joint cooperative study involving the support of the Albuquerque Projects Office of the Bureau of Reclamation, the Fish and Wildlife Service and the Army Corps of Engineers. All three agencies have been involved in several aspects of this project including floodplain mapping, river channel morphology and application of the model. The Fish and Wildlife Service has supported the Bosque floodplain mapping and the initial test application of the FLO-2D to the Isleta reach. The Isleta reach cross section survey was conducted through a joint funding effort of the Fish and Wildlife Service and the Corps of Engineers. The Corps of Engineers have performed the digital floodplain mapping used in the both the Isleta and Bosque reaches and supported the initial applications of the model. Primary funding support for Bosque del Apache Wildlife Refuge project and for the floodplain mapping was provided by the Bureau of Reclamation. The Bureau was also responsible for getting

the cross section surveys completed. All three agencies have purchased or obtained a copy of the FLO-2D model for future applications.

FLO Engineering, Inc. is an engineering contractor for the Bureau of Reclamation specializing in hydrographic data collection, river channel morphology and hydraulic engineering. Hundreds of cross sections throughout the Middle Rio Grande valley have been surveyed by FLO Engineering, Inc. The hydrographic data base compiled by the Bureau on the Middle Rio Grande includes aerial photography, ortho-photographic mapping, discharge measurements, sediment transport and bed material data and numerous cross section and floodplain surveys. These data constitute one of the best hydrographic data bases on any river in the country. From this data base, the FLO-2D model input data files will be developed.

Description of the FLO-2D Model

FLO-2D is a commercially available proprietary model created by FLO Engineering. It has been applied to numerous flood hazard simulation projects throughout the west including routing Green River seasonal flows from Flaming Gorge to the Colorado River confluence and numerous alluvial fan flood hazard delineation projects. FLO-2D is a two-dimensional, finite difference flood routing model using either a kinematic wave, diffusive wave or the full dynamic wave version of the momentum equation for unconfined, overland flow or channel flow. It simulates the progression of the flood hydrograph, conserving flow volume, over a system of square grid elements representing topography and flow roughness. FLO-2D is an ideal model for river channel overbank flooding, alluvial fan flows, flow through urban areas, or the hydraulic design of flood mitigation measures. The model has a number of components which can enhance the detail of a flood simulation including channel-floodplain discharge exchange, loss of storage due to buildings, flow obstruction, rill and gully flow, street flow, bridge and culvert flow, levee and levee failure, mud and debris flow, sediment transport, rainfall and infiltration (fig. 1). FLO-2D has been used by federal and state agencies and numerous consulting firms.

Creating a FLO-2D data base

A FLO-2D project data base requires a representation of the potential flow surface topography in a square grid format. A simple procedure has been devised with CADD software for generating the grid system. Most CADD systems contain survey routines which enable a grid system to be overlaid on a digitized map and the coordinates and elevations exported to a file. Any size grid element can be used by the model, but the timestep is governed by the wave

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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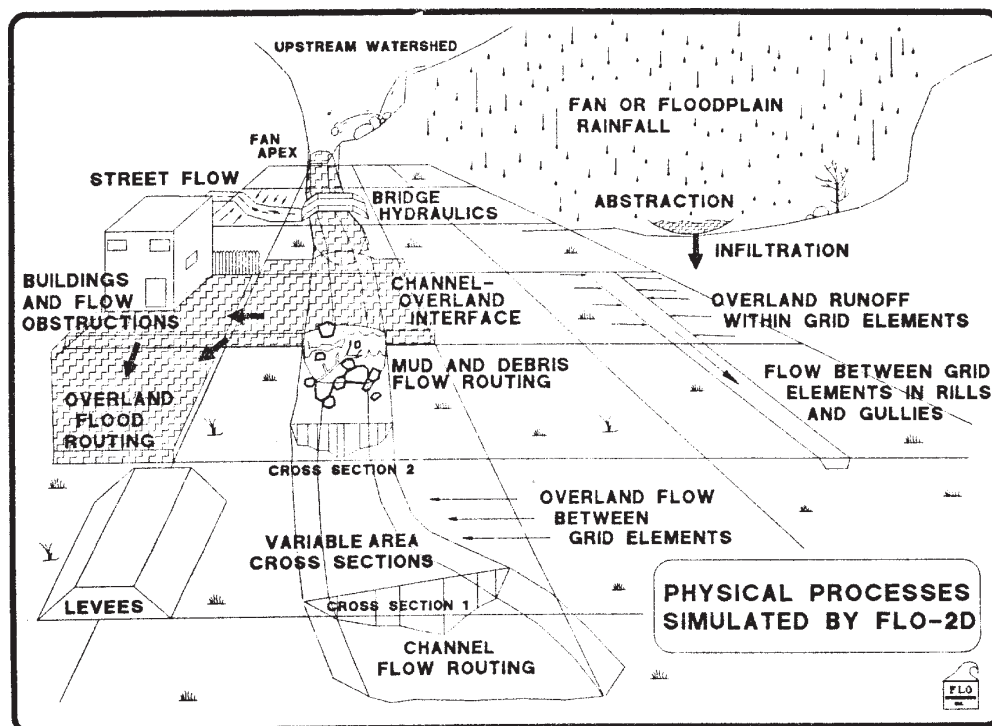


Figure 1—Physical Processes Simulated by FLO-2D.

celerity and very small grid elements will require very small timesteps. A typical grid element is 200 ft to 500 ft, but grid elements ranging from 50 ft to 2,000 ft have been used in simulations. The number of grid elements is essentially unlimited.

Routing Algorithm Stability and Volume Conservation

The timestep is incremented or decremented according to strict flood routing numerical stability criteria. Numerical stability has been linked to volume conservation which is the basis for the model accuracy. When the model accurately conserves volume, the model runs faster. If the model is gaining or losing volume, the timesteps decrease. Volume conservation is carefully tracked and is reported both during the simulation and in output files. Typically timesteps range from 1 to 60 seconds.

Overland and Channel Flow - Exchange of Channel and Floodplain Discharge

Overland flow is simulated in eight directions (4 compass and 4 diagonal directions). One-dimensional channel flow is simulated with rectangular, trapezoidal or natural shaped cross sections. A preprocessor program will convert HEC-2 cross sections into a data file formatted for FLO-2D. The channel width can be larger than the grid element allowing for more detailed floodplain simulations. When the flow in the channel exceeds the bank height, FLO-2D will compute the overbank discharge. This channel-floodplain flow interaction can occur with overland return flow to the channel

(fig. 2). This is an important component for the application of the model to the Rio Grande. The number of inflow tributaries is unlimited.

Overland flow can be concentrated in small rills and gullies as multiple channel flow. When specific grid elements are assigned multiple channels, discharge between those elements occurs as concentrated flow in small, rectangular channels and not as overland sheet flow. Rainfall on the overland portion of each grid element is routed into the element rill or gully. More than one gully can be specified for a grid element. When the rill or gully depth is exceeded, the channel is expanded by a preassigned incremental width to contain the gully flow. Variable rill and gully channel characteristics can be spatially delineated on the grid system.

Mud and Debris Flows

Hyperconcentrated sediment flow is simulated using viscosity and yield stress relationships as function of sediment concentration. Several such relationships have been analyzed in the laboratory representing different soil types and conditions. Very viscous mudflows may cease flowing on very rough surfaces or very mild slopes. Conversely, mudflows can be diluted by rainfall inflow. Storage in small debris basins and spillway discharge can be simulated.

Sediment Transport—Aggradation and Degradation

Sediment transport is computed for arid region alluvial systems using the Zeller-Fullerton equation. Almost any sediment transport relationship can be programmed into the model. For the Rio Grande bosque project, three new

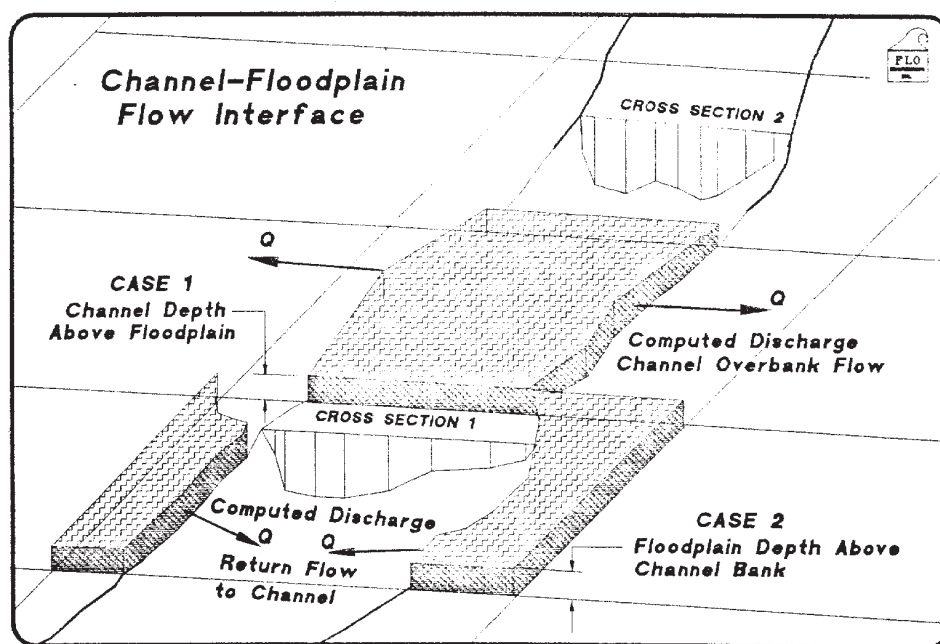


Figure 2—Channel-Floodplain Flow Interface.

sediment transport equations will be added to the model. Aggradation and degradation is predicted if the sediment transport routine is invoked. Scour and deposition are distributed uniformly on the grid element surface or channel bed.

Other FLO-2D Components

Rainfall and infiltration can be simulated on the potential flow surface before or during the flood simulation. The rainfall is then routed as overland sheet flow or as rill and gully flow until it intercepts a main channel. Infiltration is simulated with the Green-Ampt infiltration model and can be spatially variable on the flow surface.

Street discharge is simulated as flow in a shallow rectangular channel. Streets may intersect and are delineated with a width and curb height. Bridge and culvert flow on the grid system can be simulated by user specified relationships between the discharge and headwater depth.

Levees can be simulated by specifying flow directions and crest elevations. Levee failure can occur by overtopping or at a prescribed levee stage for a specified time period. Levee failure is simulated on a grid element by grid element basis.

Flow around buildings and obstructions and floodplain storage loss due to structures can be simulated on a grid element basis. A portion or the entire grid element can be removed from potential inundation. Similarly, the flow transfer between grid elements can be partially or entirely obstructed.

FLO-2D Results

Spatially and temporally varied output including flow depth, velocity, discharge hydrograph, sediment concentration and

bed elevation are written to output files. Discharge hydrographs can be established for any channel or any overland grid element in the system. Outflow grid elements can be reviewed separately. Grid elements can be grouped together as cross sections to generate flow hydrographs. Maximum depth, velocity and discharge files are automatically created. The flood progression over the flow surface can be viewed graphically along with a plot of the inflow hydrograph while the model is running. The most common desired result is a map of the maximum flow depths depicting the maximum area of inundation.

Application of FLO-2D to the Rio Grande Isleta Reach

In 1997, the Bosque Hydrology Group reviewed the potential application of the FLO-2D model to predict overbank flooding along the Middle Rio Grande. Through funding support from the Bosque Initiative and in cooperation with the Corps of Engineers Albuquerque District, the FLO-2D model was applied to a 15 mile reach of the Rio Grande downstream of the Isleta Diversion located south of Albuquerque. This reach was identified by the Corps of Engineers as a potential restoration area where overbank flooding may enhance the bosque biology.

The Corps developed a digital terrain map (DTM) and overlaid a grid system of 8,024 elements, 500 ft square (fig. 3). The river reach included 234 channel elements represented by 11 surveyed cross sections and 9 cross sections extracted from the 1995 DTM mapping. Infiltration and the levee system were modeled. Three flood hydrographs were simulated: The 250-year project flood event with a peak discharge of 42,000 cfs; the 100-year flood with a peak

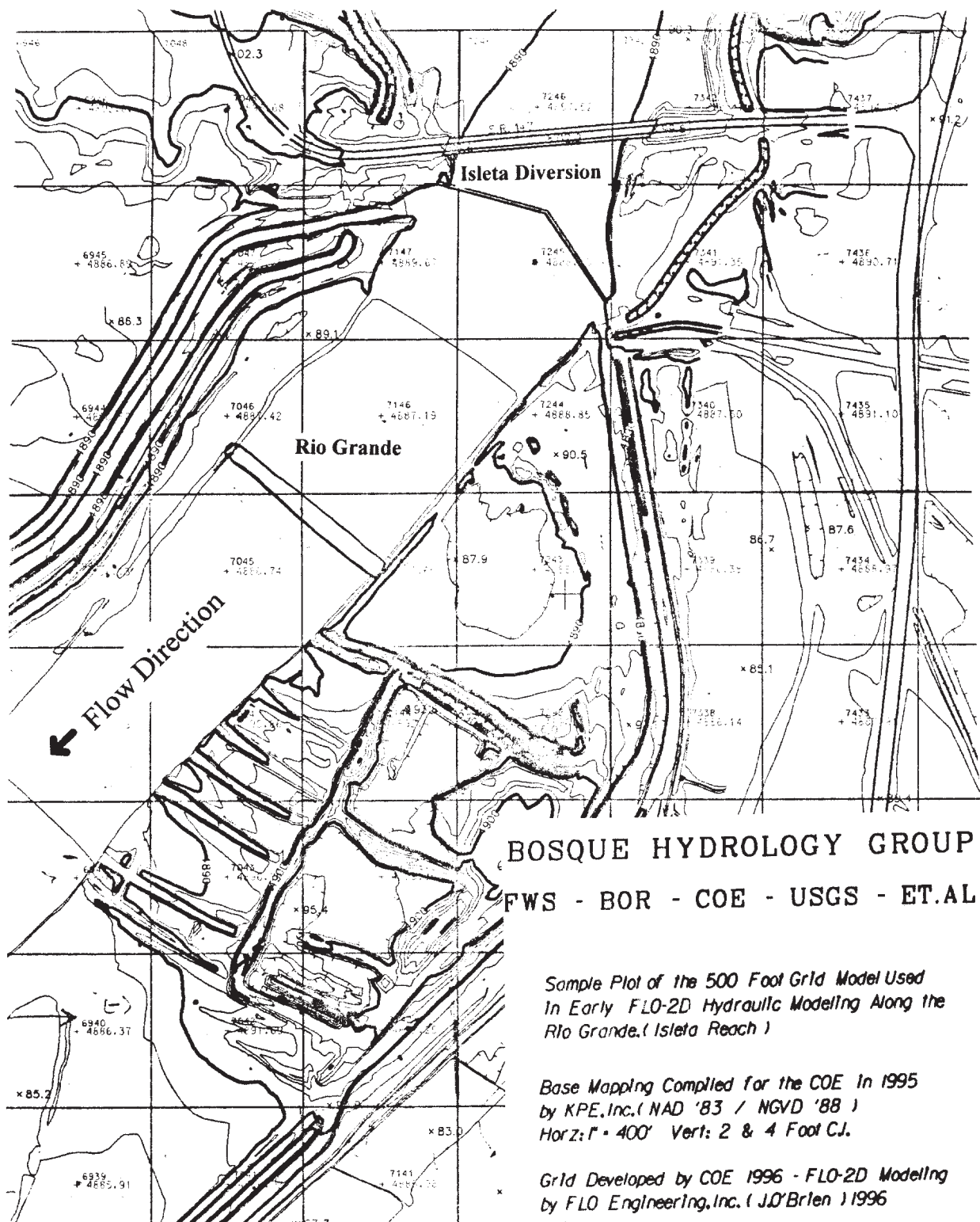


Figure 3—FLO-2D Grid System at the Isleta Diversion, Rio Grande

discharge of 15,326 cfs; and a high flow season hydrograph with a peak discharge of 7,000 cfs. The project flood event was simulated as both a levee and no-levee scenario. The spatial flood inundation results are viewed graphically when running FLO-2D or the post-processor programs.

Although this was a simple test application to determine the utility of the model for predicting overbank flooding on the Rio Grande, the results proved to be interesting. The Corps of Engineers had originally modeled this reach with HEC-2, a single discharge, one-dimensional step-backwater hydraulic model. The project flood event results essentially indicated bluff to bluff flood inundation across the Rio Grande valley for the 40,000 cfs peak discharge. FLO-2D routed the entire hydrograph and it was revealed that because the hydrograph volume was so limited, floodwave attenuation through the reach was pronounced and much of the overbank flooding was abated by the end of the reach. In the levee flood scenario, levees were overtopped in the upstream 30 percent of the reach inundating about 40 percent of the floodplain outside the levees. In the downstream half of the reach, all the overbank flooding was confined between the levees. No bluff to bluff flooding was predicted with the FLO-2D model.

Without the levees, the flood inundated approximately 50 percent of the floodplain in the reach. Most of the floodplain inundation occurred in the upstream half of the reach. Again, the floodwave attenuation was so pronounced that only a small portion of the reach was flooded. Higher floodplain depths were predicted along the eastern edge of the floodplain against the valley bluff. The results from these flood scenarios indicate that the flood hydrograph had a very limited volume. The peak discharge decreased from 40,000 cfs at the start of the reach to a predicted 25,700 cfs at the end of the reach for the levee simulation and to a predicted 15,700 cfs for the no-levee simulation. The importance of overbank flooding in floodwave attenuation is clearly demonstrated in this test. The levees increase the potential downstream flooding. If this Isleta reach is similar to the upstream reach for several miles, it is unlikely that the 40,000 cfs peak discharge would arrive at the Isleta Diversion without experiencing some attenuation.

The 100-yr flood was only simulated for the case with the levees. All of the overbank flooding was contained between the levees. A portion of the channel in the lower third of the reach conveyed all the flow. There was no predicted overbank flooding for a reach of approximately two miles. The 100-yr hydrograph peak discharge did not significantly attenuate.

The final flood simulation involved the high flow seasonal discharge related to spring runoff of 7,000 cfs. In this flood scenario, the areas of floodplain inundation were of primary interest. Most of the upstream half of the reach was inundated, but only about one-third of the downstream half of the reach was flooded. Channel conveyance capacity was greater in the lower portion of the river reach. There was no significant floodwave attenuation.

The test application of FLO-2D to the Isleta reach proved successful in several aspects. First, it was ascertained that the model could successfully identify which reaches might be preferable for overbank flooding. Secondly, the test demonstrated the importance of routing the flood hydrograph. Timing and flow duration will be critical to assess overbank

flood potential in reaches further downstream of Isleta. Given a prescribed volume as a flow augmentation release from Cochiti Dam to enhance overbank flooding, the release hydrograph can be adjusted to maximize either flood duration or area of inundation in various reaches. Finally, the FLO-2D simulation highlighted several drawbacks in the existing Isleta Reach data base.

Accurate prediction of floodplain inundation along the Rio Grande is contingent on three important factors; adequate DTM mapping (both in topographic accuracy and contour resolution), appropriate cross section spacing and calibrated roughness parameters. Through the FLO-2D Isleta application, it was determined that the eleven surveyed Cochiti cross section lines provided by the Bureau and recently re-surveyed by FLO Engineering did not match the extracted DTM cross sections developed by the Corps of Engineers. The two sets of cross sections were out of phase (they weren't surveyed in the same season) and Corps cross sections did not represent a complete picture of the channel (thalwegs were estimated). As a result, when the Isleta reach model was developed, some grid elements had adverse bed slope conditions and inappropriate roughness Manning's n-values. Cross section and n-value adjustments were made to permit the model testing to proceed, but it became apparent that additional data collection was necessary to upgrade the Isleta reach data base to obtain reliable results. Specifically, the following hydrographic data collection will be required:

- Additional cross sections are needed in transitional reaches where the channel changes from a narrow to a wide cross section.
- All the cross sections should be surveyed in a relative short period of time during a period of high flows to avoid the effects of scour and fill in a reach.
- Water surface elevations should be surveyed at all the cross sections during a relatively short period in conjunction with a discharge measurement to calibrate the n-values during high flow.

It is anticipated that these data will be collected during this spring runoff to enable the Isleta Reach to be accurately modeled with FLO-2D to predict potential overbank flooding.

Prediction of Flow Hydrographs Using FLO-2D

The National Park Service and the Fish and Wildlife Service Denver Office supported the development of a FLO-2D discharge routing model for the Green River in Utah from Flaming Gorge Dam to the confluence of the Colorado River, a distance of 412 miles. The FLO-2D model was proposed as hydrograph routing tool to support flow recommendations for the Flaming Gorge biological opinion being written by the Fish and Wildlife Service. To develop the routing model, a digital topographic map was prepared, all available Green River cross section surveys were compiled and inflow hydrographs were assembled. This included seasonal high flow hydrographs of Flaming Gorge Dam releases and the tributary inflow of the Yampa, Duchesne, White, Price, and San Rafael Rivers as well as Brush and Ashley Creeks.

The project goal was to use FLO-2D to predict the seasonal flow hydrograph at any location in the Green River downstream of Flaming Gorge Dam on a daily basis. The project objectives included:

- Calibration of the model for the 1996 high flow season.
- A review of the model accuracy by simulating the 1997 high flow data.
- An estimate of floodplain inundation area for these two flow years.
- Simulation of the Flaming Gorge jet tube releases.
- Prediction of discharge timing and duration at any location in the Green River.

Green River flows were simulated for 100 days of the 1996 high flow season beginning on April 1 and ending on July 9. In 1996, five level loggers for monitoring river stage were established throughout the Green River system. Combined with the USGS gages at Jensen and Green River, they constitute a system of seven known discharge points with which to calibrate the FLO-2D predicted hydrograph.

A 2,000 foot square grid system was overlaid on the digitized base map resulting in 2,482 grid elements of which 962 were designated as channel elements. A total of 268 surveyed cross sections were analyzed for channel geometry relationships and assigned to the channel elements. Channel roughness and infiltration parameters were adjusted within acceptable ranges to calibrate the predicted hydrograph at the seven points of known discharge in the Green River. Generally, the final Manning's n-value ranged from 0.024 to 0.050 with the higher n-values assigned to grid elements in the steep canyon reaches. Some channel element cross sections and roughness values were adjusted to reduce the abrupt transition between grid elements. The assigned cross sections created adverse slope conditions for some elements in the channel profile. For these elements, the channel depth and bed elevations were adjusted to achieve a uniform reach slope.

FLO-2D predicted a hydrograph for every channel grid element (every 2,000 ft) throughout the Green River system from Flaming Gorge to the Colorado River confluence. The 1996 measured hydrographs were used to calibrate the model and then FLO-2D was applied to 1997 flows using the same channel data base. Excellent correlation was achieved between the FLO-2D predicted hydrograph and measured discharge hydrograph at the USGS Jensen gage located at one-third of modeled river system (fig. 4 and 5). Further downstream at the USGS Green River gage (about two-thirds through the system), there was some disparity between the predicted and measured discharge hydrographs (fig. 6 and 7). The differences between the predicted and measured hydrographs were attributed to:

- Small unmeasured tributary inflow between Jensen and Green River.
- Storm inflow reflected in spikes in the measured discharge.
- Canal diversion at Green River, Utah.
- Estimated discharge reported for the Green River gage (discharge record errors).
- Variable infiltration and evaporation losses in the reach from Jensen to Green River.

Despite these correlative discrepancies, the USGS Green River gage data compared very favorably with the FLO-2D predictions.

The utility of the FLO-2D model was further demonstrated by simulating flows without the storage effects of Flaming Gorge reservoir and by adjusting Flaming Gorge Dam releases. These simulations indicated a substantial increase in floodplain inundation when Flaming Gorge releases were timed to occur with the peak discharge in the Yampa River. This application of FLO-2D to the Green River illustrated the flexibility of the model as a management tool.

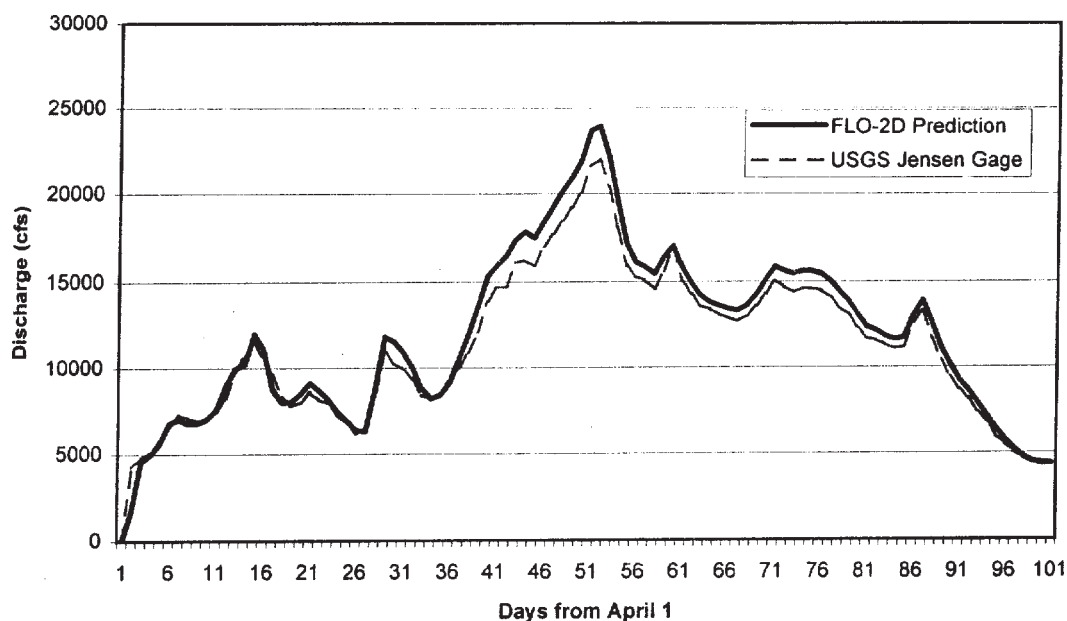


Figure 4—1996 Green River Hydrograph at Jensen, Utah

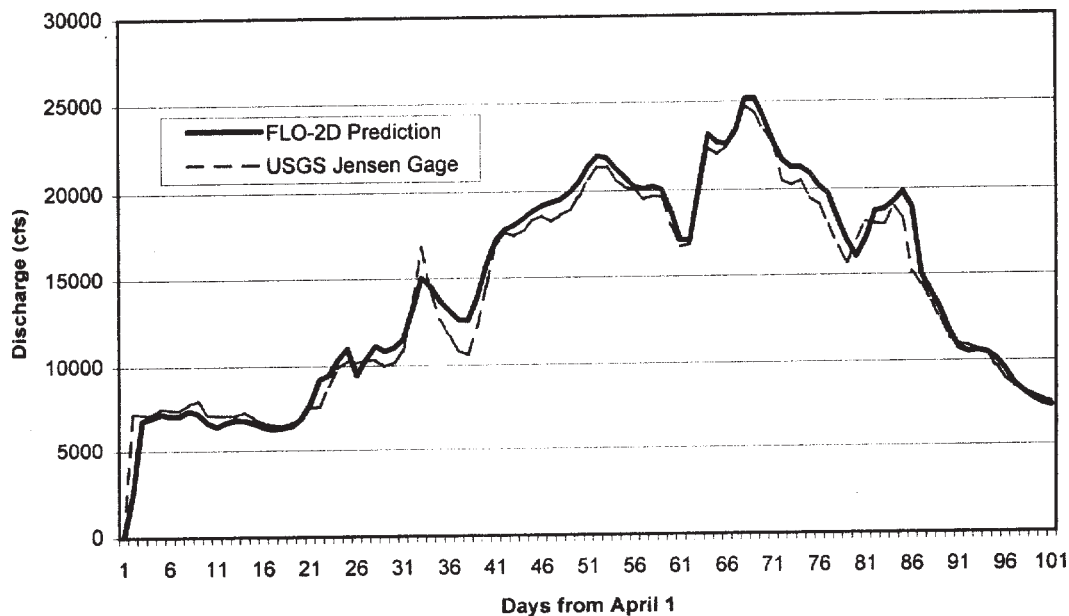


Figure 5—1997 Green River Hydrograph at Jensen, Utah

Application of the FLO-2D

Through the cooperation of the Albuquerque Projects Office of the Bureau of Reclamation, Corps of Engineers, and the Fish and Wildlife Service, the FLO-2D model will be applied to a 20 mile reach of the Rio Grande near the Bosque del Apache National Wildlife Refuge south of San Antonio, New Mexico. The modeled reach will extend from the Highway 380 bridge to the south boundary of the refuge. This project will encompass several aspects of the Rio Grande

hydrology and channel morphology. The goal of the project is to design a seasonal high flow hydrograph that will inundate selected areas of the floodplain in this reach. The high flow hydrograph will be analyzed in terms of its frequency and flow duration. Initially, FLO-2D will be used to simulate flow with a rigid boundary model. In subsequent applications, FLO-2D will simulate channel flow with a mobile bed. Several sediment transport models will be tested and calibrated.

Preparation of the FLO-2D data base for Bosque reach began last year when a series of 41 cross sections were

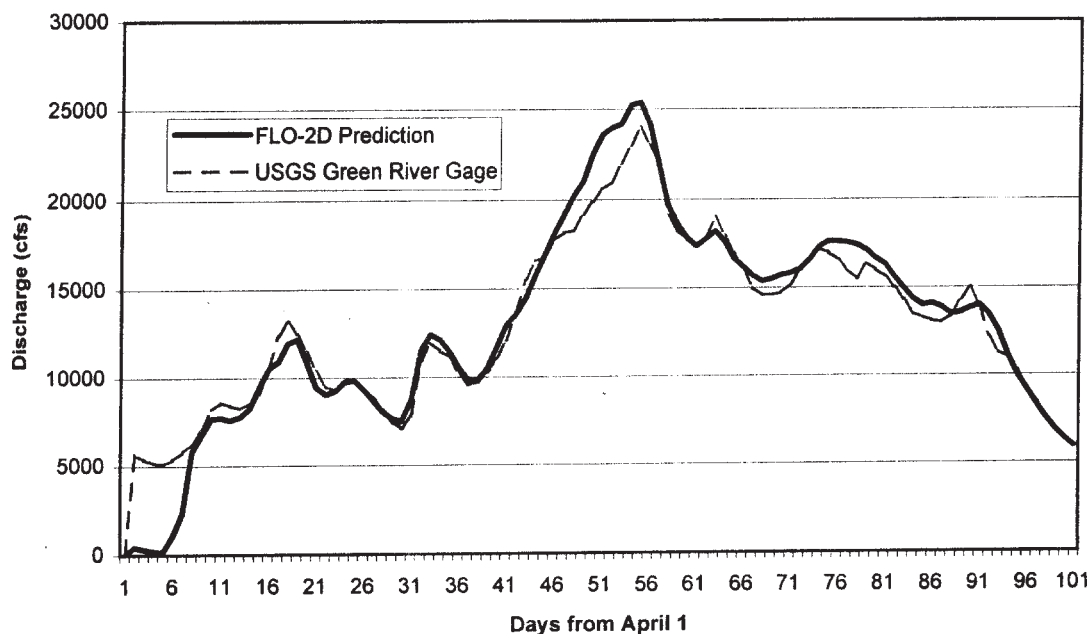


Figure 6—1996 Green River Hydrograph at Green River, Utah

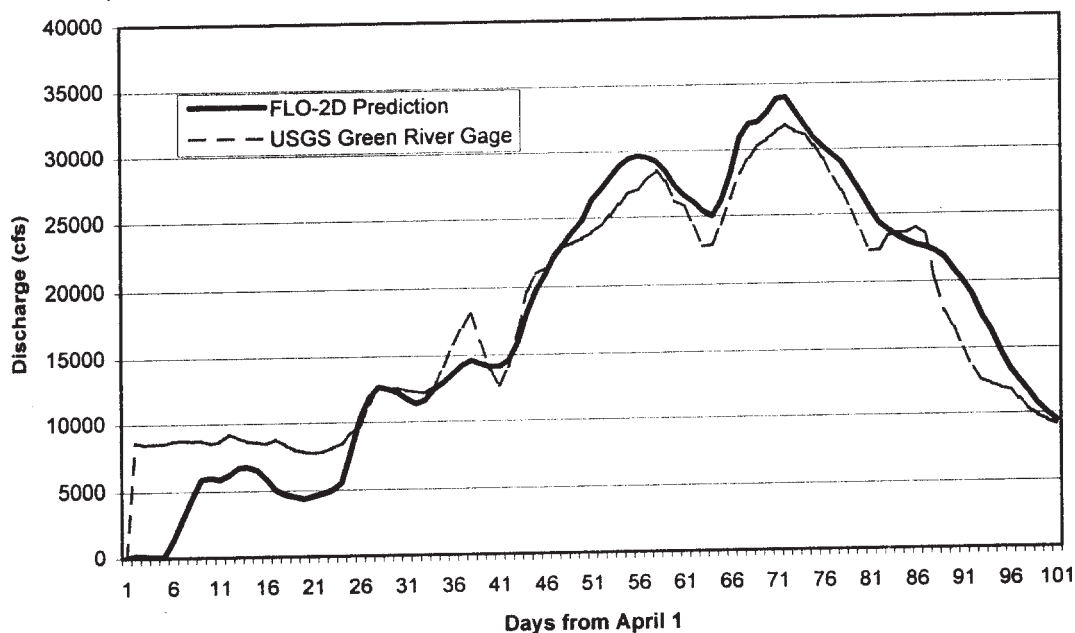


Figure 7—1997 Green River Hydrograph at Green River, Utah

surveyed in the study reach. The majority of these cross sections have been surveyed several times over the last decade. Twelve new cross sections were established in transition reaches from a narrow to a wide channel. A digital map of the floodplain with 2 foot contours has been completed from aerial photogrammetry by the Corps. On this base map, a 500 ft square grid element system will be overlaid for the FLO-2D model. The base map can be used by all researchers participating in the Bosque Initiative. In addition, water discharge, sediment load, bed material sizes, water surface elevations, aerial photos of overbank flooding and other hydrographic data have been collected over the past several years which will be applied to calibrate the model. Three flow hydrographs will be simulated:

- 10-year average hydrograph (peak discharge ~ 4,500 cfs)
- 2-year return period hydrograph (peak discharge ~ 8,470 cfs)
- Low flow period hydrograph (peak discharge ~ 3,500 cfs)

An important part of this project will be the model calibration to existing data bases. In several locations along this reach, bed scour reduces the propensity for overbank flooding during high flows. At 3,000 cfs, the water surface in certain locations may be within a half foot of being bankfull. Later in the hydrograph at a flow of 5,000 cfs, the water surface elevation may be foot below the top-of-bank. This channel bed response is difficult to predict because it depends on sediment supply as well as flow hydraulics. The Bureau has developed a total load rating curve which will be applied as the sediment supply to the study reach. One project objective will be to determine the importance of channel bed response to high flows in terms of the area of inundation. Generally, the volume of the water stored in the channel at a given time is relatively minor compared to the total volume in the flood hydrograph, however, changes in

channel cross section and conveyance can significantly impact the location at which overbank flow occurs. For this reason, both a rigid bed and mobile bed analysis will be conducted with the FLO-2D model. At least three sediment transport equations will be used in the model calibration.

It is anticipated that the model data base will be developed during this summer and the project will be completed by the end of 1998. The final product of this flood routing project will be an area of floodplain inundation versus discharge relationship that might be incorporated into reservoir operation and Rio Grande flow management to promote overbank flooding near the Bosque del Apache National Wildlife Refuge. The FLO-2D results and projected flood inundation maps combined with projections of the Rio Grande hydrology can be the basis for decisions regarding frequency, duration and timing of high flows. This project objective is a focal point of the proposed Rio Grande bosque restoration. If the FLO-2D simulations are successful, there is interest in developing the FLO-2D model for the entire Middle Rio Grande from Cochiti Dam to Elephant Butte Reservoir.

Conclusions

The FLO-2D model will be used to investigate the potential for limited overbank flooding along various reaches of the Middle Rio Grande to enhance the natural functions of the bosque biological community and to increase opportunities for cottonwood tree germination. Overbank flooding will be evaluated in terms of river discharge, timing, frequency and duration. The model has demonstrated its utility on the Isleta reach illustrating the importance of simulating floodwave attenuation. In an application for the Green River in Utah, the FLO-2D model accurately replicated season hydrographs measured in various locations throughout the

river system. In the coming year, the Isleta reach simulation will be finalized and the model will be applied to a 20 mile reach of the Rio Grande near the Bosque del Apache National Wildlife Refuge. The results of the model will include area of inundation versus discharge/duration relationships which can be used to investigate various combinations of reservoir releases and operations.

Acknowledgments

The application of the FLO-2D model to the Middle Rio Grande is a cooperative effort of the Fish and Wildlife

Service, Bureau of Reclamation and Corps of Engineers. The primary participants in this effort include Paul Tashjian and Jeff Whitney of the Fish and Wildlife Service, Drew Baird of the Bureau of Reclamation, and Doug Wolf and William DeRagon of the Corps of Engineers. Support for this project came from all three agencies with the Bureau of Reclamation being the primary source of funding. The Bosque Initiative provided the initial impetus to examine the potential for applying the FLO-2D model to the Isleta Reach. The Bosque Hydrology Group of the Bosque Initiative is central forum for discussion, direction and review of the FLO-2D simulations.

Upper Rio Grande Water Operations Model: a Tool for Enhanced System Management

Gail Stockton
D. Michael Roark

Abstract—The Upper Rio Grande Water Operations Model (URGWOM) under development through a multi-agency effort has demonstrated capability to represent the physical river/reservoir system, to track and account for Rio Grande flows and imported San Juan flows, and to forecast flows at various points in the system. Testing of the Rio Chama portion of the water operations model was completed in March 1998. Results indicate that RiverWare software can be used to model the entire upper Rio Grande system. Model development is in progress on the mainstem of the Rio Grande.

The process of moving water through the Rio Grande basin has become increasingly complex. In 1996, six federal agencies recognized the need for a tool that could help them make timely decisions and improve storage and delivery operations in the Upper Rio Grande Basin for more effective and efficient system management. They needed a computer model with accounting and forecasting capability that could simulate near real-time reservoir operations. The agencies agreed in a memorandum of understanding to cooperate to develop a model for the upper Rio Grande basin from the headwaters in Colorado to Fort Quitman, Texas and to provide access to actual, forecasted, and planned reservoir and river operational data through a unified data base for data management and information sharing among basin stakeholders.

As a result of 1997 model scoping and coordination activities with other basin interests, the cooperating agencies finalized a plan for development of the Upper Rio Grande Water Operations Model (URGWOM). The plan identified computer software (RiverWare) and associated hardware that could be used in developing the model and outlined the tasks and schedule for model development.

Cooperative Effort

Since 1996, the Bureau of Reclamation (Reclamation), U.S. Fish and Wildlife Service, U.S. Geological Survey (U.S.G.S.), Bureau of Indian Affairs, the International Boundary and Water Commission (U.S. Section), and the U.S. Army Corps of Engineers (Corps) have partnered to develop the model. The cities of Albuquerque and Santa Fe, Rio Grande Restoration, Sandia and Los Alamos National

Laboratories also entered into this partnership in 1997. Other entities, as well, have contributed to the effort through technical review and outreach support.

The cooperative spirit of this effort is exemplified by the co-located modeling team with members from Reclamation, U.S.G.S., and the Corps working together and sharing a melange of computer equipment and also by the technical review team made up of stakeholders, interested individuals, and state, local, and federal agency staff who have contributed many hours of technical review of the test case.

Rio Chama Test Case

To test that RiverWare was capable of simulating the entire Upper Rio Grande surface water system, the software was first tested on the Rio Chama. This stream reach was selected because of its operational complexity. It includes a transmountain diversion, three reservoirs with complex operational criteria and accounting procedures. Because it has relatively simple river reach conditions and reasonable availability of data, it was a good test of the capabilities of the software.

RiverWare

RiverWare is a generic reservoir and river system modeling software that can be readily customized to fit a specific river basin. It has been in development since 1993 and is the result of a continuing collaborative effort by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado, the Bureau of Reclamation and the Tennessee Valley Authority.

RiverWare is object oriented, meaning that the software has objects that represent features of the basin visually on a computer screen such as reservoirs, confluence's, gaging stations, river reaches, diversions, data, etc. Objects contain user selected physical process methods and numerical data. For example, the modeler can specify different routing method categories for a stream reach object: "no routing", time lag, Muskingham-Cunge, kinematic wave, etc. Variables called "slots" contain all the data that are required or generated by the object. In the case of a stream reach, a reach object may contain slots for inflow, return flow, outflow, and other data.

The software is referred to as data-centered because data supplied to the model defines the specific river and reservoir system. It is also rule-based; operating policies are incorporated into the model with a rules language. RiverWare uses the operational rules to make decisions during a simulation. None of these customizing features requires a change in the hard code of the software so it is easily modified for changes

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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in policies or addition of new objects as the basin changes. Since the data and rules defines the specific system, the Rio Chama test case model was developed by entering Rio Chama data and rules.

The software also has multiple calculation methods that can be selected to customize the physical behavior of an object. For example, there are about eight different calculations available to choose from for calculating spills from a reservoir, everything from no spill to a complex combination of regulated spill plus bypass plus unregulated spill calculation. In the specific case of Abiquiu Reservoir, the no spill calculation was selected to represent the real situation. After the objects are put into a workspace and the appropriate methods are selected they can be linked together to form a river basin network.

The most recent improvement to RiverWare was the addition of the water accounting function. Each object has accounts slots for accounting data.

Conceptual Model Development

The Technical team began model development of the Rio Chama by describing the existing physical and water accounting systems, graphically and in text, to serve as a basis for the construction of the model in RiverWare. Public technical review and comments on the conceptual model documents were provided by the Technical Review Committee.

Physical Model

The physical model of the test case is a rule-based simulation of the physical system of the Rio Chama. The model simulates the physical system from the top of the basin, starting with the San Juan diversions and continuing downstream to the confluence of the Rio Chama with the Rio Grande at Chamita. Figure 1 shows the topology or layout for the Rio Chama in RiverWare. The Technical Team built the computer version by constructing each object separately: first, reservoirs; then, river reaches; followed by confluence's and diversions. Each object was verified by comparing to historical data. After all objects were built, verified and linked together, the over all model was checked against records for a period from January 1985 to July 1996. Simulated results closely matched actual records. The resultant physical model represents the Rio Chama physical system and is the basis for the test case accounting and forecasting models.

Accounting Model

The accounting model incorporates water ownership and accounting functions into the physical model. It is essentially a data processing and reporting application of the model structure. The layout for the accounting model is displayed in figure 2. Since the water input data for San Juan Chama Project accounting is measured at the outlet of the Azotea tunnel, the San Juan diversions are not shown as objects in the topology for the accounting model. However, the rest of the physical model structure is used in the accounting model.

The accounting model solves for inflow since the releases from the reservoirs are measured and are direct inputs to the model. It is designed to perform the same operations that Reclamation's daily water operations programs perform, and to eliminate many of the hand calculations that are presently needed to distinguish San Juan water from Rio Grande. Additionally, it can simulate the two types of water accounting in the river reaches between reservoirs. By mid 1999, the model will also be capable of simulating San Juan Chama contractors accounts.

Forecast Model

The forecast model is used to simulate the operation of the river and reservoir system by determining releases and storage for a desired forecast period. Since it is based on the physical model, includes the accounting functions of the accounting model, and the rules based upon water operations regulations, constraints and preferences, it is a very powerful tool to understand the system. The topology of the forecast model is shown in figure 1.

Forecasted inflow hydrographs at all of the forecast points and the initial conditions of the reservoirs are required inputs to the model. The forecast model using the rules, simulates how varying hydrologic conditions upstream may affect water operations downstream. It simulates most routine water operations and clearly defined special operations, including emergencies, thus giving water managers the ability to make timely decisions.

Test Case Results

Figures 3, and 4 display few differences between the test case model and Reclamation's daily program calculations of inflow and precipitation at Abiquiu Reservoir for 1985 to 1996. Comparisons of the two methods gave similar results for outflow, and evaporation at Abiquiu and at the other reservoirs.

Figure 5 shows the cumulative differences between the two methods in storage at Abiquiu Reservoir. The total cumulative difference between using the model to compute storage versus using the daily programs is about 46 acre feet, a small cumulative error for 10 years of record. Total storage capacity for Abiquiu Reservoir at elevation 6220 feet is 189,307 acre feet.

The test case model forecast of total outflow at Abiquiu Reservoir is compared with historical data for a 10-month period of record in figure 6. The model simulations for San Juan outflow and Rio Grande outflow also closely duplicate the historical data. Historical time series data were used as inputs at the upstream forecast points for these simulations.

Testing, therefore, indicated that the software RiverWare successfully modeled the Rio Chama and could be used on the mainstem of the Rio Grande. Since the test case contained most of the physical components such as diversions, river reaches, confluences, and hydropower that will be encountered in the remainder of the upper Rio Grande Basin, a great number of operational rules and accounting relationships have already been worked out to some degree for the mainstem model development.

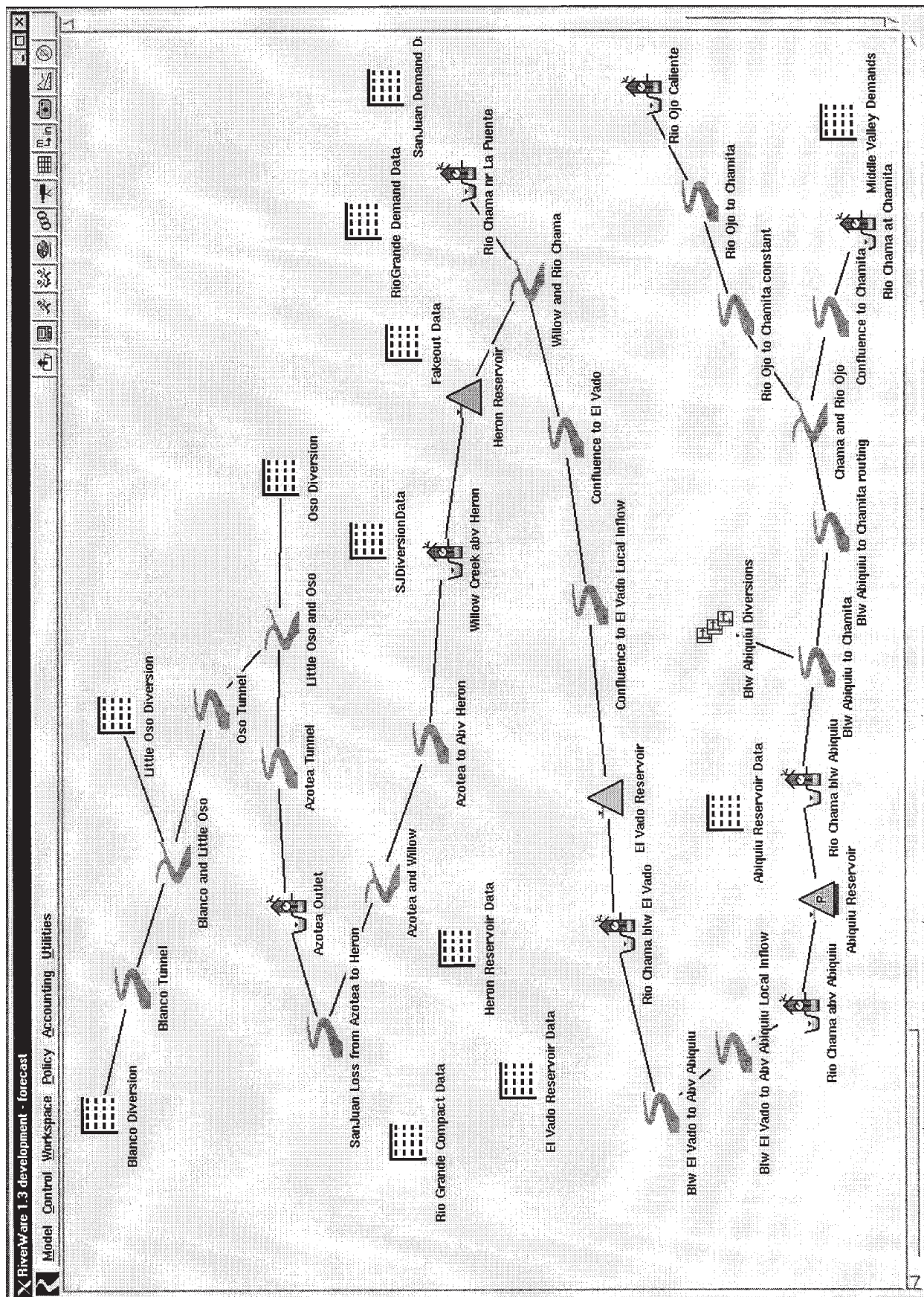


Figure 1

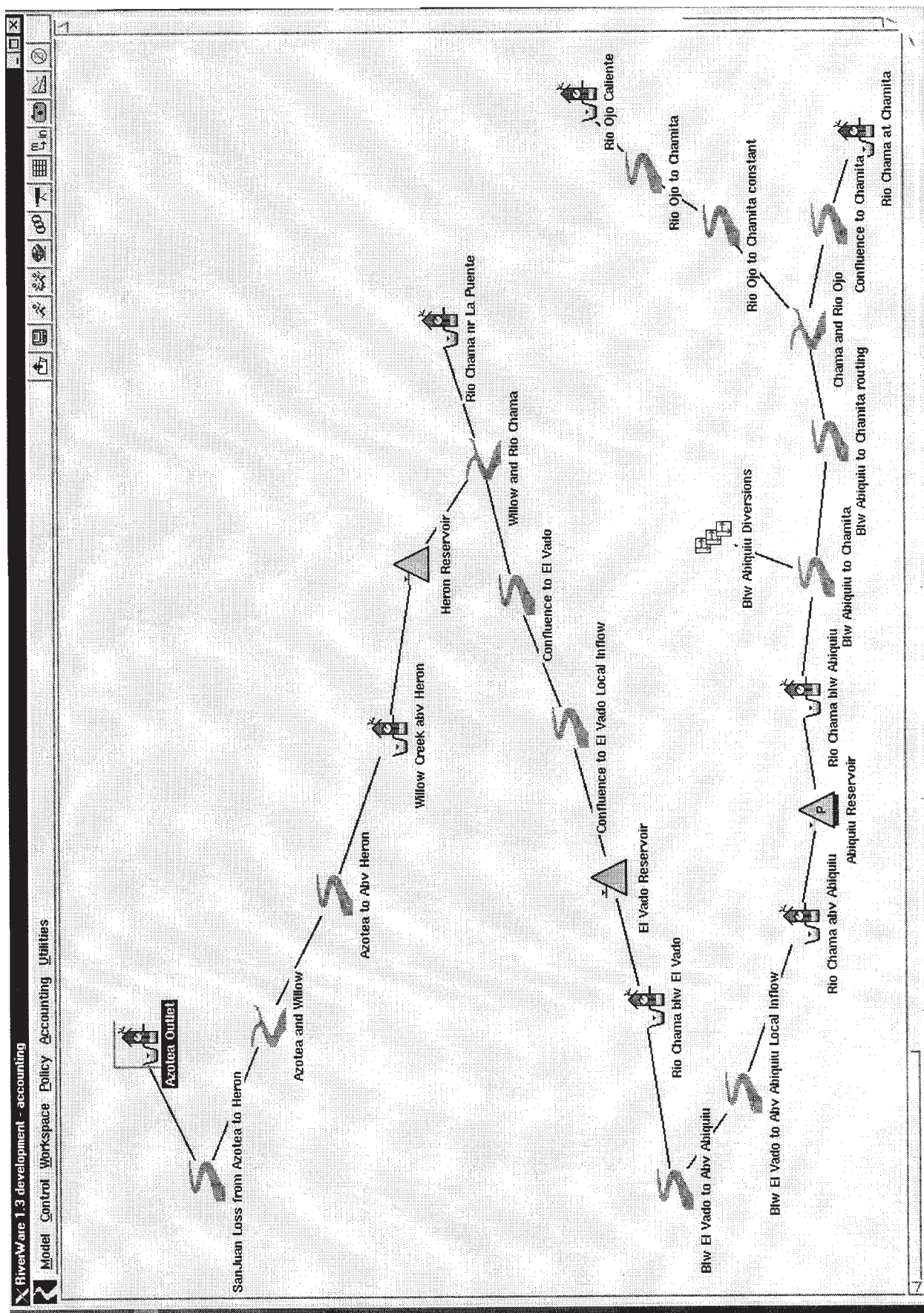


Figure 2

Abiquiu Reservoir (Solved for Inflow) - Difference in Inflow Between Daily and RiverWare

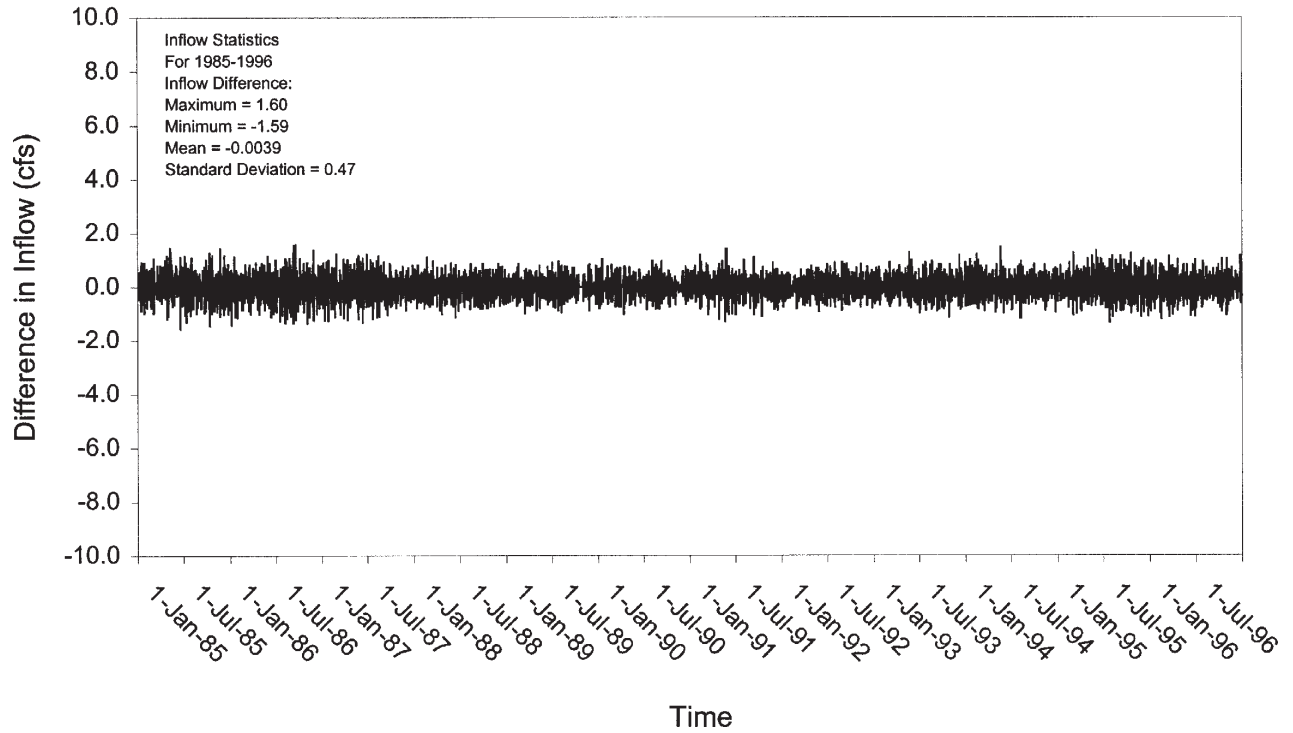


Figure 3

Abiquiu Reservoir (Solved for Storage) - Difference in Precipitation Between Daily and RiverWare

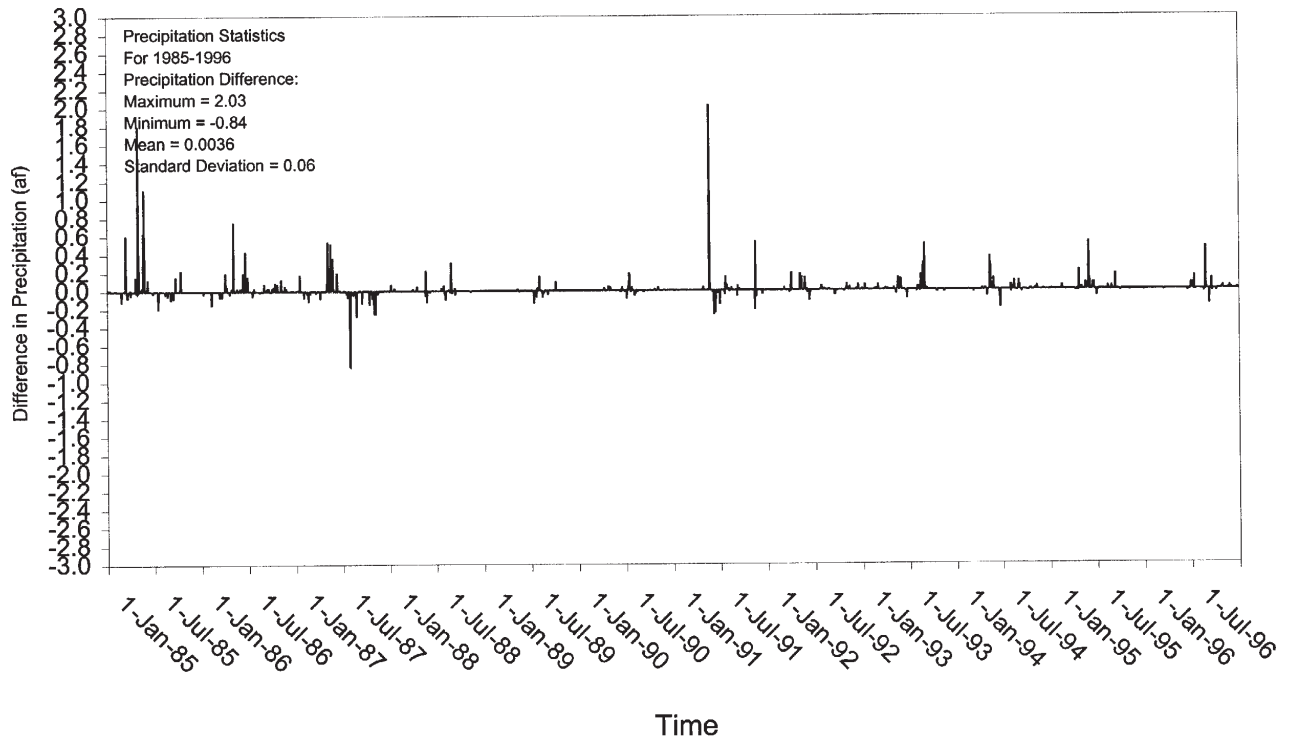


Figure 4

Abiquiu Reservoir (Solved for Storage) - Difference in Storage Between Daily and RiverWare

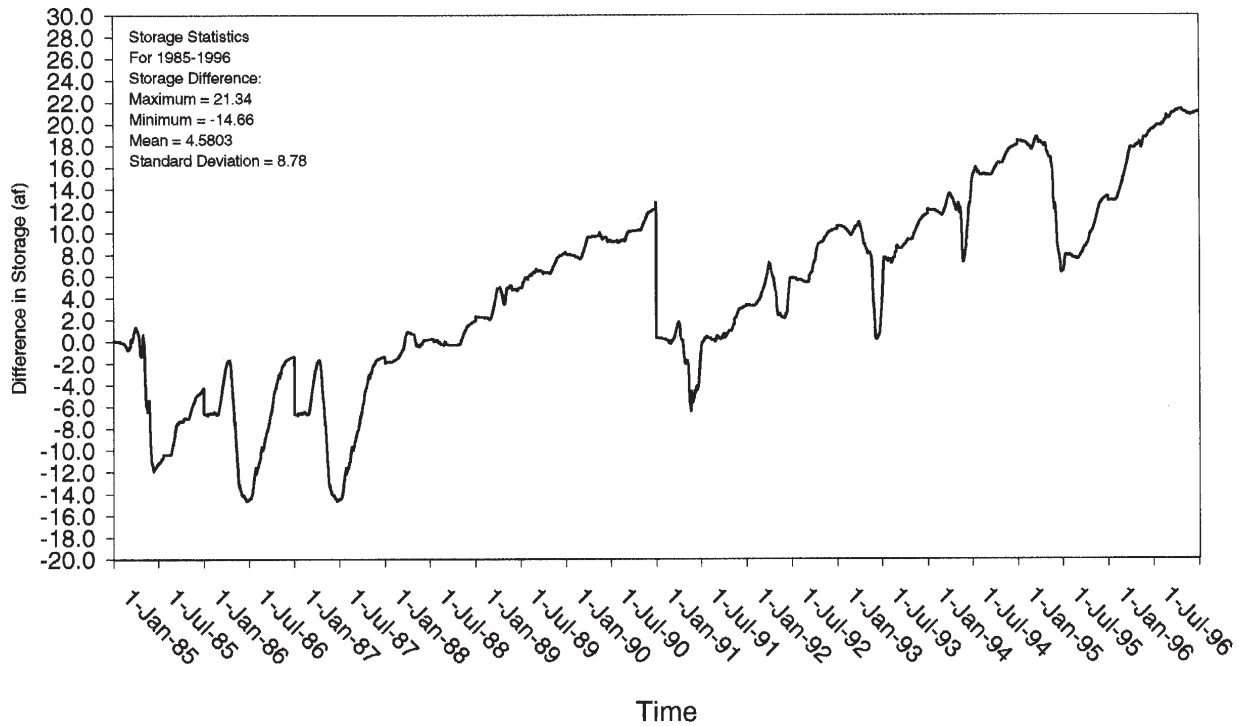


Figure 5

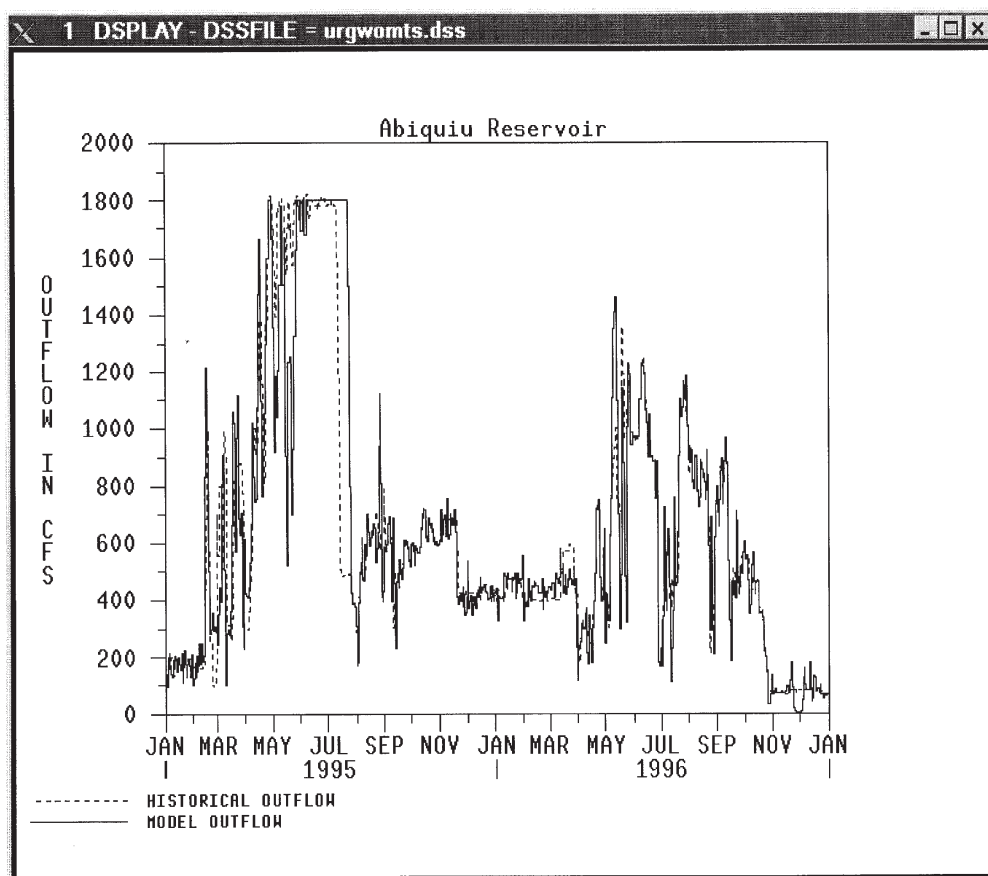


Figure 6

Mainstem Model Development _____

Following the completion of the test case in March 1998, the Technical Team began the conceptual model of the mainstem. Expected completion date of a functioning, but not exhaustively calibrated and verified basic water operations (or "backbone") model of the upper Rio Grande is Fall 1999. The fully refined model completion date is approximately 2002.

Data Base and Other Tools _____

While URGWOM is under development, the Technical Team is utilizing the Corps Data Storage System (DSS) to format and store data. The team has written data management interface programs (DMI)s that interface the time series data stored in DSS with the Rio Chama model for use in testing and calibrating. The same will be done for the mainstem since DSS is easy to use. Part of the Technical Team is investigating needs and requirements for an URGWOM Data Base. The Corps Hydrologic Engineering Center provided a cursory screening of data base alternatives. Their preliminary report indicated that Reclamation's HDB has potential to serve URGWOM's ultimate data storage needs.

An URGWOM data base will store time series data, spatial data, and accounting data. A unified data base will provide a source of data for and from URGWOM that will be accessible for use by anyone needing the data. It will be a resource for other models such as planning models, as well as a source of data for URGWOM model applications.

Water Operations Review

One of the applications of URGWOM is the Upper Rio Grande Basin Water Operations Review (Water Operations Review). This is a joint effort with Reclamation to take an integrated look at the system. Part of this effort will be to develop supplemental tools or models, that with input from URGWOM, can determine what effects potential water operations changes have on riparian vegetation, aquatic communities, endangered species, cultural resources, and other basin resources. The review will likely be a five-year effort, starting in 1999.

References _____

- Bureau Of Reclamation; U.S. Army Corps of Engineers; U.S. Geological Survey; in Cooperation with: U.S. Fish and Wildlife Service; Bureau of Indian Affairs; International Boundary and Water Commission (U.S. Section). 1997. Upper Rio Grande Water Operations Model Plan for Development. Albuquerque, NM. 96 p.
- Bureau of Reclamation and others. 1997. Conceptualization of the Test Case Reach of the Upper Rio Grande Water Operations Model Part I - Physical Model (Draft). Albuquerque, NM. 58 p.
- Bureau of Reclamation and others 1997. Conceptualization of the Test Case Reach of the Upper Rio Grande Water Operations Model Part II - Water Accounting and Ownership (Draft). Albuquerque, NM. 65 p.
- The Center for Advanced Decision Support for Water and Environmental Systems; University of Colorado at Boulder; RiverWare CADSWES-USBR Training: Simulation Modeling, June 3-5, 1997. Boulder, CO.
- Bureau of Reclamation; U.S. Army Corps of Engineers; Preliminary Plan of Study Upper Rio Grande Basin Water Operations Review. 1998. Albuquerque, NM. 5 p.

Salinity Management in the Rio Grande Bosque

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Abstract—This paper discusses management options for salinity control in the Rio Grande Bosque. First, salt sources are identified and quantified. Capillary rise of ground water is the most important cause for soil salinization in the bosque. Next, a riparian salt balance is presented to explain the different mechanisms for soil salinization. Finally, the advantages and disadvantages of three salinity control options are discussed: drainage systems, adaption to natural conditions, and managed flooding.

The Rio Grande has two important functions. One is to deliver water to aquatic and terrestrial habitats as well as to urban and rural communities linked by the river; the other is to transport salts and other wastes generated by those habitats and communities to the Gulf of Mexico.

Until the beginning of this century an apparent salt balance existed in the Rio Grande Valley. The accumulation of salts in the soils adjacent to the river was counteracted by frequent inundations that provided surplus water for salt leaching. Infrequent major floods resulted in a reshaping of the river landscape and reallocation of salt sinks. Construction of flood protection and irrigation works since the early 1900's have resulted in a more regular river flow without major flooding events. In addition, much river water has been allocated for agriculture, wetlands, and domestic and industrial water supplies. The combined effects of decreasing river water supplies and channelization of the river to a permanent streambed have resulted in environmental conditions where soil salinity is no longer controlled by the river (for example Crawford and others 1993; Conover 1954).

Since soil salinity determines to a large extent the success of revegetation projects in the Rio Grande Bosque management measures are needed to control soil salinity levels. The objective of this study is to discuss management options for salinity control in the Rio Grande Bosque.

Salt Sources

A good understanding of salt sources in the Rio Grande Bosque is needed for the development of effective salinity

control options. Five salt sources contribute to the salinity of riparian areas under natural vegetation: atmospheric deposition, mineral weathering, capillary rise, seepage from higher areas West and East of the river, and flooding.

Atmospheric deposition in the interior of most continents is about 40 kg/ha (Bresler and others 1984). *Mineral weathering* is an important process that affects the chemistry of waters in rivers, soils, and shallow ground water. It involves the dissolution, alteration, and precipitation of minerals and for the most part takes place in the zone of aeration of soils. Since the mineral weathering rate of a given soil is proportional to the amount of water that flows through the soil (Langmuir 1997), it will increase with the leaching fraction. Rhoades and others (1973, 1974) and Wierenga and others (1972) studied in lysimeters the compositions of drainage waters resulting from irrigation with eight synthesized river waters of the Western USA under conditions of alfalfa production on calcareous and noncalcareous sandy loams. For Rio Grande water, leaching fractions above 25 percent resulted in a net increase of salts in the drain water by approximately 2-10 percent of the salts in the irrigation water. When the leaching fraction is less than 25 percent, salt precipitation will occur and will result in a decrease of salt content in the drainage water. These percentages indicate that the contribution of mineral weathering to soil salinity in the bosque is of the same order of magnitude as atmospheric deposition.

The most important salt source at many locations is *capillary rise* which results from upward water flow originating at the ground water table. The amount of capillary rise depends on the depth of the ground water table and the physical characteristics of the soil profile. Table 1 presents capillary characters in a number of homogeneous soil profiles. For example, a ground water table depth at 2 m will result in capillary fluxes of 0.2 mm/day in a sand soil and 8 mm/day in a loamy sand. Even if the ground water quality is good, such rates can result in considerable salt depositions near the soil surface or in the root zone. For example, ground water with a total amount of dissolved solids of 500 mg/l will accumulate 5 kg of salts per hectare for each millimeter of capillary rise. This results in an annual salt load of, respectively, 365 and 14,600 kg/ha in the previously mentioned sand and loamy sand soils.

Salt accumulation by capillary rise will rapidly decrease if the ground water table is lowered. However, in many cases the ground water table remains relatively shallow as a result of *ground water seepage*. Such seepage may originate from higher areas West and East of the river or from man-made sources. An example of man-made seepage is found at

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Table 1—Maximum capillary rise (cm) for five fluxes (cm/day) in homogeneous soil profiles (Hendrickx and others 1990).

Texture	Capillary Flux (cm/day)				
	2.0	1.0	.6	.1	.01
Sand	69	82	92	135	213
Loamy Sand	151	185	213	334	572
Sandy Loam	29	45	61	158	484
Loam	73	99	123	247	577
Silty Loam	59	90	121	321	1025
Clay Loam	126	165	197	342	639
Silty Clay Loam	7	12	18	65	219

Santa Ana Pueblo where surplus irrigation water from the golf course on the mesa is seeping into the lower lying riparian area. Another more important example are the wetlands created to provide food and shelter for migratory birds. The flooding of wetlands and the irrigation of adjacent agricultural fields result in shallow water table depths around the ponds and an increase in salinization as a result of capillary rise. This can be observed in the Bosque del Apache, La Joya, and San Bernardo reserves.

Another salt source is *flooding* since the water in the Rio Grande contains approximately 300 to 500 mg/l total dissolved solids (Crawford and others 1993). This means that a flood of 0.5 m water would deposit 150 to 250 kg salt per hectare.

The most important salt source in riparian areas is capillary rise since its potential contribution exceeds by far the salt amounts originating from atmospheric deposition, mineral weathering, and flooding. Areas with relatively shallow ground water tables (1 to 3 m) that discharge ground water seepage have the highest risk for salinization.

Riparian Salt Balance

Salinization will occur when the amount of salt added to the soil by rain water and flood water is greater than the amount of salt removed by drainage waters. The salt balance of the riparian root zone can be expressed as

$$R.C_r + F.C_f + G.C_g = P.C_g + \Delta S \quad [1]$$

where R is rainfall entering the root zone (mm/year), C_r is the salt concentration of the rain water (mg/l), F is the amount of flood water entering the root zone (mm/year), C_f is the salt concentration of the flood water (mg/l), G is the amount of capillary rise into the root zone (mm/year), C_g is the salt concentration of the ground water, P is the amount of deep percolation or drainage water leaving the root zone and entering the ground water, and ΔS is the amount of salt stored in the profile. It is assumed that the salt concentration of the drainage water and capillary rise water is equal to the salt concentration of the ground water which is quite reasonable for annual periods but less so for shorter periods.

Equation [1] reveals several important aspects of riparian salinity balances. Firstly, soil salinization becomes inevitable if no drainage takes place to evacuate the salts from the root zone, i.e. if $P=0$ then ΔS will increase. Without some form of drainage soil salinization cannot be prevented even if the irrigation or flood water contains only

small amounts of salt. Of course, under the latter conditions salinization would take a long time.

We have found evidence in the Bosque del Apache that older soils contain more salts than younger ones. The age of soils can be approximately determined from aerial photographs by observation of channel continuity and the degree of organic matter and aeolian dust accumulation which are reflected in soil color. The oldest river deposits show complicated patterns of channel breaches and different degrees of organic matter and aeolian dust accumulation. The younger deposits show more continuous channels and less diversity in soil color.

Using these criteria we selected two locations with comparable point bar deposits and water table depths, but different estimated ages of isolation from the active river. At both sites soil salinity was measured at several hundreds of points using electromagnetic induction (for example Hendrickx and others 1992; Sheets and others 1994). Average topsoil salinity in the younger deposits was 24 against 280 mS/m in the older deposits. Average subsoil salinity was 31 mS/m in the younger deposits and 225 mS/m in the older. This shows a ten fold increase in soil salinity for comparable deposits in terms of soil texture and depth to the groundwater as a result of age, i.e. the duration during which capillary rise has contributed to salt accumulation in the soil profile.

Secondly, flooding only will lead to a decrease of soil salinity if the flood water leaches out salts, i.e. if $P>0$ so that the salts percolate into the ground water and can be transported towards a drain. Otherwise, the salts in the flood waters actually will contribute to an increase in soil salinity. Whether flooding will result in drainage depends on the water retention and hydraulic conductivity of the soil profile. Before drainage occurs the root zone needs to be sufficiently wetted to allow downward flow. In most riparian areas with shallow ground water tables this requirement will not pose a problem. In addition, the hydraulic conductivity of all soil layers must be large enough to allow the drainage water to pass through. This requirement poses serious limitations on the use of flooding in soils that contain clay layers with a low permeability. In such soils the flood water will become perched on the clay layer. A large part of the perched water will evaporate or transpire while leaving the salts behind in the root zone and, thus, increase soil salinity. This scenario is quite common in riparian areas. Another important factor that determines the effect of flooding is the leaching efficiency. For an effective leaching it is not sufficient to replace once all soil water by flood water. On the contrary, the soil should be flushed several times to make it salt free (Hoffman 1980).

For example, in the Bosque del Apache on soil unit 29 natural regeneration of cottonwood is being stimulated by applying an annual flood of approximately 0.3 m. The flood water carries cottonwood seeds that settle at the high water lines. After several weeks seeds emerge and young trees start growing. In unit 29, the soil profile consists of a layer of 50 cm to 100 cm of sandy loam to loamy sand overlying clay loam to clay. Before flooding the soil water content in the top 40 cm and from 40 to 80 cm is, respectively, 3 and 9 volume percent. The soil water content in the underlying clay loam is close to saturation. During flooding the soil water content increases to saturation which is approximately 35 volume percent. This means that

$(0.35-0.03)*40 + (0.35-0.09)*40 = 23.2$ cm water will be stored in the top 80 cm of the soil profile during flooding. Most of this water will evaporate during the gradual infiltration of the flood water into the soil and contribute little to salt leaching. Instead it will add to the salt load. The total amount of water stored in the soil profile at unit 29 is about 30 cm. This means that an efficient leaching will require at least 60 to 90 cm of water.

The relatively low permeability of the subsoil of unit 29 and the small amount of flood water applied have resulted in an increased salinity after flooding. Salinity measurements before flooding in April 1997 and after flooding in August 1997 revealed an increase of soil salinity from 150 to 262 mS/m in the subsoil and from 112 to 204 mS/m in the topsoil. Standard deviations of the measurements were high, indicating considerable variability from place to place.

A third aspect of equation [1] is the importance of capillary rise. Since the salt concentration of the ground water is at least one order of magnitude larger than that of rain water, even a relatively small capillary flux, G , can cause a large increase of soil salinity. Under the arid conditions of the Rio Grande Valley it is a constant challenge in riparian nature reserves to maintain a water balance in which the deep percolation rate exceeds the capillary upward flux. Without such condition no favorable salt balance can be maintained.

Salt Management Options

The physical principles for salt management in soils are well understood (Bresler and others 1984, Smedema & Rycroft 1983; Van Schilfgaarde 1974) and lead to three basic strategies for salinity management in the Rio Grande bosque: (1) Installation of drainage systems; (2) Adaptation to natural conditions; (3) Managed flooding.

Installation of drainage systems is the classical response to salt problems in irrigated agriculture. The functions of a drainage system are to lower the ground water table and to discharge saline drainage waters percolating from the root zone. The ground water table is lowered to a depth at which the upward capillary flow becomes too small for any significant upward salt movement. This depth depends on the soil type and can vary from 50 cm in a coarse sand to more than 400 cm in loamy soils (see also table 1). A drainage system can consist of surface drains or of underground pipes (Smedema and Rycroft 1983; Van Schilfgaarde 1974). The outlet is the terminal point of a drainage system where it discharges into the river.

In mountainous terrain with large elevation differences drainage waters can be discharged by gravity but in many arid river valleys the slope of the land surface is not sufficient to drain by gravity. For example, the gravity system installed near Las Nutrias (New Mexico) performs only marginally since sufficient head is not available to discharge the drainage waters. Therefore, it is common practice to have the drain waters accumulate in a sump and to discharge by pumping. Such a system has been in use until a few years ago in the Bosque del Apache. Although the system performed well during a period of about fifteen years, it has been shut down and will be not be replaced. The main reasons for this decision are: (1) The initial installation costs are high (approximately \$200,000 for 120 acres); (2) The life of the system was shorter than expected due to clogging of the

Table 2—Relationship between cottonwood tree vigor class and soil salinity (Hendrickx and others 1997).

Tree vigor class	N	Salinity (mS/m)			
		Mean ^a	Std Dev	Minimum	Maximum
Healthy Tree	30	60a	25	25	140
Marginal Growth	23	111b	64	24	225
Dying Tree	28	210c	112	85	534

^aMeans with the same letter are not significantly different.

tile drains; (3) The system was difficult to maintain (John Taylor, personal communication 1998). These complaints are typical even in large irrigation projects with trained personnel.

DralZage systems work well for moist soil management and agricultural fields covering large areas. However, due to high costs and problematic maintenance their use for restoration of native vegetation appears limited.

Adaption to natural conditions involves identifying optimal locations for revegetation of native species such as cottonwoods. Hendrickx and others (1997) conducted a systematic study near El Paso and statistically confirmed the dependence of cottonwood survival on soil salinity level (table 2). They also observed a close relationship between geomorphology and soil salinity. The lowest levels often were found on small levees which naturally are the preferred areas for cottonwoods. The highest levels occur in depressions such as old river channels with a fine soil texture that enhances capillary rise.

At the Rio Bosque Park near El Paso it was found that 50 percent of the variability in salinity could be explained by soil type and ground water table depth. This indicates that in areas with soil and ground water table maps the location of suitable restoration areas is relatively straightforward. Otherwise an inexpensive salinity survey using electromagnetic induction can quickly indicate the areas with revegetation potential (Sheets and others 1994).

Managed flooding is often propagated as an efficient and natural way to restore cottonwood and other native vegetation. Flooding can only be successful for restoration if it contributes to an effective salinity control. This requires (1) a soil profile of sufficient permeability for salt leaching and (2) sufficient quantities of flood water. If either of these factors is not fulfilled, flooding will not lead to sustainable restoration.

Managed flooding is a relatively inexpensive method to control soil salinity and to promote bosque restoration. However, the design of a flood management plan requires detailed knowledge of the interaction between flood water, ground water, soil, and vegetation.

References

- Bresler, E., McNeal, B.L. & Carter, D.L. 1982. Saline and sodic soils. Principles-dynamics-modeling. Springer Verlag, New York.
- Conover, C.S. 1954. Ground water conditions in the Rincon and Mesilla valleys and adjacent areas in New Mexico. U.S. Geological Survey Water-Supply Paper 1230.
- Crawford, C., A.C. Cully, R. Leutheuser, M.S. Sifuentes, L.H. White, J.P. Wilber, and R.E. Robino. 1993. Middle Rio Grande ecosystem: bosque biological management plan. Biological Interagency Team. U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

- Hendrickx, J.M.H., M. Akram Chaudhry, J.W. Kijne, M. Sadiq, and Iqbal Raza. 1990. Soil physical measurements for drainage design in arid regions. Symposium on Land Drainage for Salinity Control in Arid and Semi-Arid Regions, Febr. 25-March 2, Cairo, Egypt. Vol. 2:124-134.
- Hendrickx, J.M.H., B. Baerends, Z.I. Raza, M. Sadiq, and M. Akram Chaudhry. 1992. Soil salinity assessment by electromagnetic induction on irrigated land. *Soil Sci. Soc. Am. J.* 56:1933-1941
- Hendrickx, J.M.H., J. Beekma, R. Koch, G. Rodriguez-Marin. 1997. Salinity survey for revegetation potential along the Rio Grande in the Paso del Norte region. Report to the El Paso Field Division of the U.S. Bureau of Reclamation.
- Hoffman, G.J. 1980. Guidelines for the reclamation of salt affected soil. In: O'Connor (ed) 2nd inter American conference on salinity and water management technology, Juarez Mexico. pp 49-64.
- Langmuir, D. 1997. Aqueous environmental geochemistry. Prentice Hall, Inc.
- Rhoades, J.D., R.D. Ingvalson, J.M. Tucker, and M. Clark. 1973. Salts in irrigation drainage waters: I. Effects of irrigation water composition, leaching fraction, and time of year on the salt compositions of irrigation drainage waters. *Soil Sci. Soc. Am. Proc.* 37:770-774.
- Rhoades, J.D., J.D. Oster, R.D. Ingvalson, J.M. Tucker, and M. Clark. 1974. Minimizing the salt burdens of irrigation drainage waters. *J. of Environm. Quality* 3:311-316.
- Sheets, K.R., J.P. Taylor, and J.M.H. Hendrickx. 1994. Rapid salinity mapping by electromagnetic induction for determining riparian restoration potential. *Restoration Ecology* 2:242-246.
- Smedema, L.K. and D.W. Rycroft. 1983. Land drainage. BT Batsford Ltd, London.
- Van Schilfgaarde, J. 1974. Drainage for agriculture. Agronomy Series #17, American Society of Agronomy, Madison, WI.
- Wierenga, P.J., G.A. O'Connor, and H.E. Dregne. 1972. Soil and water management for salinity control. New Mexico Water Resources Research Institute Report No. 018.

Albuquerque's Constructed Wetland Pilot Project for Wastewater Polishing

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Abstract—The City of Albuquerque has funded the Constructed Wetland Pilot Project (CWPP) since 1995 at the City's Southside Water Reclamation Plant (SWRP). Results from CWPP and other wetland treatment projects indicate that appropriately designed surface-flow wetlands could increase the cost-efficiencies of wastewater treatment, as well as help the City meet present and future discharge limits for nitrate, ammonia, organic nitrogen, various metals, biological oxygen demand, and total suspended solids, among other constituents. Results from CWPP also support the option to construct a 5-acre or larger demonstration-scale treatment wetland that would provide increased realism for evaluating the effectiveness of wetland polishing and potential habitat benefits.

The City of Albuquerque City Council and the City's Public Works Department have funded the Constructed Wetland Pilot Project (CWPP) located at the City's Southside Water Reclamation Plant (SWRP). The CWPP started July 1, 1995 to provide a pilot-scale evaluation of constructed treatment wetland effects and potentials to provide cost-effective "polishing" (i.e., enhanced treatment) to improve the quality of the City's wastewater discharges. Present and future design-flow capacities for the SWRP are, respectively, 60- and 76-million gallons-per-day (mgd). This study has been assessing alternative wetland treatment strategies that may help the City meet National Pollutant Discharge Elimination System (NPDES) discharge limits to address increasingly stringent water quality standards for the Rio Grande. These standards are established by the New Mexico Water Quality Control Commission and by the Pueblo of Isleta, located five miles downstream from Albuquerque. The initial goal of the CWPP was to use the information collected to help decide whether to conduct a larger demonstration-scale study and/or begin construction of a full-scale wetland treatment facility for the "polishing" of SWRP's effluent.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

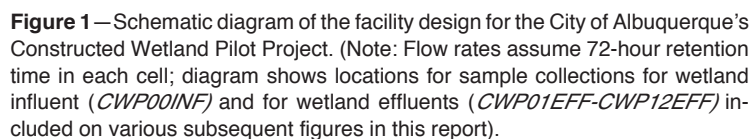
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Constructed wetlands have been found to provide viable alternative treatment components to conventional "concrete-and-steel" wastewater treatment systems (U.S. EPA 1988). These wetlands include *free-water surface* (open-water) systems, with surface flows through shallow water depths, and *subsurface flow* systems, with water flowing laterally through sand and gravel. Constructed wetlands provide cost-effective treatment to meet wastewater discharge requirements for many municipal discharges and for other discharges across the U.S. and around the world (Albuquerque-Bernalillo Constructed Wetlands Study Group Report 1993, Hammer 1989, Kadlec and Knight 1996, Moshiri 1993, and U.S. EPA 1988). Because of the construction and operation cost savings possible, the number of municipalities benefitting from constructed wetland treatment technologies has increased. In the Southwest, for example, only four constructed wetlands treating municipal wastewater existed in Arizona during 1990 and 15 existed in 1994. By 1997 Arizona had 26 municipal and onsite constructed wetlands operating, with an additional 24 wetlands either awaiting approval or under construction (Anonymous 1997, Gelt 1997).

Natural wetlands, which include swamps, bogs, sloughs and marshes, are often described as "nature's kidneys" to characterize the water quality improvements produced in waters flowing through these systems (Mitsch and Gosselink 1986). Constructed wetlands are similar to natural wetlands. Both involve communities of wetland plants, associated microorganisms, and chemical reactions in the water and soil substrates to purify water. Also, constructed wetlands are similar to conventional wastewater treatment facilities. Both are technologically-based designs that strive to enhance natural processes to cleanup wastewater. But, because constructed wetlands rely much less on concrete and steel (and more on land surface area), construction and operation costs are often much lower for wetland facilities having comparable treatment capabilities. For example, compared to the \$360 to \$625 million that officials estimated as needed to upgrade Phoenix's 91st Avenue Wastewater Treatment Plant, the projected cost of developing the existing \$3.5-million Tres Rios Constructed Wetland Pilot Project into a full-scale facility was an additional \$80 million (Gelt 1997, Greeley and Hansen 1996). That is, upgrading the wetland treatment system was projected to cost only 13 to 22 percent of the cost for a concrete and steel upgrade to the plant to meet the same water quality goals.

plans for the 800-acre Tres Rios constructed wetland project in Phoenix include accommodations for more than a half-million visitors annually expected to access the recreational and educational features of the project (Tres Rios Recreation Technical Committee 1997).

Albuquerque's CWPP facility includes 12 individual open-water (surface-flow) wetland treatment cells, each is 102-feet long and 40-feet wide (fig. 1). The constructed wetland cells cover about 1.1 acres. Four wetland plant species were planted in duplicated plantings across six pairs of these cells to monitor effects by these communities on



water quality, water loss through evapotranspiration, and incidental habitat attributes. The water source for the wetland is treated, dechlorinated SWRP effluent, which is diverted to the wetland shortly upstream from the conveyance structure carrying SWRP effluent to the Rio Grande. The SWRP effluent is then distributed to the surface of the wetland cells. For most of the study, wetland flows were single-pass, through the length of the cells, before being discharged at the ends opposite from the inflows through a French-drain located along the bottom of the cells. Final effluents from most wetland cells are recycled back into the SWRP's treatment waters.

Starting in March 1997, the effluents from Cells 9 and 11 were directed into Cell 7, and the effluents from Cells 10 and 12 were directed into Cell 8. This was done, not to address specific treatment issues, but to allow greater latitude to increase flow volumes to Cells 9 through 12. The effluent flows from 7 and 8 are then recycled back into the SWRP. Operation of the wetland facility has focused on maintaining a 3-day target hydraulic retention time in each of the cells, with water depths ranging from 6 to 36 inches, as appropriate for the plant species inhabiting each wetland cell. Under the target hydraulic retention time, total target flow to the wetland facility was approximately 115 gallons-per-minute (gpm), 0.17 mgd, and 185 acre-feet per year.

Sampling was conducted from June 1996 through May 1998 to assess the removal efficiencies in each wetland cell for parameters of potential concern for future NPDES discharge limits. Of particular concern, ammonia, nitrate plus nitrite, total organic nitrogen, biological oxygen demand, and total suspended solids samples were collected every two weeks for analyses. Every four weeks, metals samples were collected to assess silver, aluminum, and arsenic removals. All analyses were conducted at the City of Albuquerque, Public Works Department, Water Quality Laboratory.

Treatment wetlands generally include a series of wetland cells, rather than the parallel, single-pass wetland flows studied in the CWPP. Each cell in the series typically has different vegetation types, water depths, and hydraulic retention times to produce different environmental conditions that sequentially address different water quality restoration issues. Selection of vegetation types used in these sequenced wetland cells often includes consideration of the potential ecological benefits of the plant communities to both aquatic and terrestrial animals.

In a simplified example, treatment wetlands constructed to address nitrogen removal commonly hold a community of larger emergent plants (for example, bulrush) in the first treatment cell. These cells commonly contain very low to no oxygen in the shallow waters surrounding the plants to aid nitrate removal. Such conditions also aid the breakdown of organic materials, converting organic nitrogen to ammonia. The second community in the treatment series is often a deeper, open-water, often pond like area, where ammonia discharged from the previous wetland cells is converted into nitrate. Next, a second emergent community often serves largely as a filter to remove suspended algae and other material, before the wetland water is discharged. The discharge structure for the wetland can produce additional water quality effects. Figure 1 provides an expanded but still simplified characterization of water quality effects possible through a series of wetland cells having different vegetation and treatment characteristics.

When reviewing and assessing the results from the CWPP, it is very important to understand that the design and

operation of this facility have produced conditions that test effects on water quality produced by alternative wetland communities that might be used as the first wetland treatment component, as described in figure 2. In a full scale wetland facility, effluents from wetland cells, which had been designed and operated like the CWPP cells, would commonly discharge into a series of subsequent wetland cells for additional treatment, very commonly through sequenced oxic (oxygen containing) and anoxic (oxygen lacking) water conditions. Thus, the water quality effects reported in the following sections represent example results from a range of water quality changes obtainable with passage through *only* the first wetland cells from a possible series of additional wetland communities. Because the CWPP cells represent, in effect, only the first part of what could be some potentially larger treatment wetland design, their results are best characterized as likely representing the low to average range of the treatment benefits possible for SWRP effluents using wetland polishing. The water quality conditions in effluents from the CWPP cells reported here cannot be extrapolated to represent either the best or final water quality results obtainable for SWRP effluents using constructed wetland treatment.

Results and Discussion

Hydrology Characteristics in the Wetland Cells

Hydraulic flow regimes in the wetland cells were relatively consistent during 1997, reasonably approaching target 3-day retention times. During 1996, hydraulic consistency and integrity of the wetland cells were compromised due to problems with the wetland's influent delivery system and holes in the liners of the wetland cells caused by muskrats that colonized the facility. The improved 1997 results occurred, first, because of improvements to the influent plumbing that were installed and maintained by the wetland staff. Second, removal and exclusion of muskrats from the facility allowed successful patching of holes in the wetland liners.

Water Quality Changes in Routine SWRP Discharges

Focusing on the period from March to November 1997, the observations and results from this project show the following:

Silver concentrations in SWRP effluents and CWPP influents for 1997 both averaged 0.6 µg/l (fig. 3). During this period, average effluent concentrations from wetland Cell 5 (3-square bulrush) were less than the potential 30-d average NPDES limit of 0.21 µg/l for a 76-mgd discharge. Statistical analyses indicate that Cell 3 (spikerush), Cell 5, and Cell 7 (open-water/ duckweed) produced effluent silver concentrations that were significantly less than influent concentrations. Greatest variability in silver effluent concentrations occurred in Cell 4 (spikerush), Cell 8 (open-water/duckweed), and Cell 1 (mixed species), respectively. (Recall that effluents from Cells 9 - 12 provided the influents to Cells 7 and 8.) Statistical analyses also indicate there was no significant difference in net removal of silver among the wetland cells, i.e., no cell was particularly better at removing

EMERGENT MARSH 1:	FREE-WATER SURFACE:	EMERGENT MARSH 2:	DISCHARGE (NPDES):
Bulrush, cattails Anaerobic/reducing water Water depth - 4 to 8 inches (ave.) 1 to 2 feet (max)	Pond - submerged plants Aerobic/oxidizing water Water depth - 30-60 inches (ave. to max.)	Bulrush, cattails Anaerobic/reducing water Water depth - 4 to 8 inches (ave.) 1 to 2 feet (max)	Open-water/cascade Aerobic/oxidizing water Water depth - 2-12 inches (ave. to max.)
<u>Concentration Reductions:</u>	<u>Concentration Reductions:</u>	<u>Concentration Reductions:</u>	<u>Concentration Reductions:</u>
BOD/COD Dissolved oxygen Suspended Solids (TSS) Pathogens NO ₃ ⁻ (plant uptake; denitrification ----> N ₂ + N ₂ O) Complex Organics (ammonification ----> NH ₃) Many/Most Metals (sulfide ppt., filtration)	NH ₃ (volatilization; nitrification ----> NO ₃ ⁻) NO ₃ ⁻ (plant uptake) Complex Organics (oxidation and photo-decomposition) BOD/COD Some Metals (Sorption)	Suspended Solids (TSS - algae and duckweed) NO ₃ ⁻ (plant uptake; denitrification ----> N ₂ + N ₂ O) Complex Organics (ammonification ----> NH ₃) BOD/COD Dissolved Oxygen Pathogens Additional Metals (sulfide ppt., filtration)	NH ₃ (volatilization; nitrification ----> NO ₃ ⁻) NO ₃ ⁻ (plant uptake) H ₂ S Complex Organics (volatilization, oxidation and photo-decomposition)
<u>Concentration Increases:</u>	<u>Concentration Increases:</u>	<u>Concentration Increases:</u>	<u>Concentration Increases:</u>
NH ₃ H ₂ S (Chlorination, optional)	NO ₃ ⁻ algae & duckweed Wildlife habitat value and use (Non-human pathogens may increase)	NH ₃ H ₂ S	Dissolved Oxygen (Chlorination, UV, or Ozonation)

Figure 2—Common design components (cells) and typical functions for a free-water surface constructed treatment wetland.

silver than another cell. The variability for silver in CWPP effluents suggests that some recurring analytical interference or sample contamination problem (for example, entrained particles) may have produced high concentration spikes.

Aluminum in SWRP effluents and CWPP influents averaged 82.6 and 98.6 µg/l, respectively (fig. 3). Average effluent concentrations from all wetland cells, excluding Cell 3 (spikerush), produced effluent concentrations that averaged less than the pending 30-d average low flow NPDES discharge limit of 60 µg/l for aluminum during 76-mgd discharges. Statistical analysis indicated that all cells during this period, except Cell 3, produced effluent aluminum concentrations that were significantly less than wetland influent concentrations. Greatest variability in aluminum effluent concentrations occurred in Cell 3. Statistical analyses also indicate that no cell was significantly better at removing aluminum than another cell.

Arsenic concentrations in SWRP effluents and CWPP influents averaged 7.0 and 7.1 µg/l, respectively (fig. 3). Both values are less than the existing 30-d average limit for arsenic of 13.7 µg/l. Cell 5 (3-square bulrush) produced the minimum average effluent arsenic concentrations. This effluent averaged 5.1 µg/l, which is markedly greater than a potential 30-d average NPDES discharge limit of 0.031 µg/l for low-flow 76-mgd discharges. Statistical analysis of the wetland effluent arsenic concentrations indicated that effluents only from Cells 5 and 6 (both 3-square bulrush cells) were significantly less than concentrations in wetland influents. Statistical analysis also indicated that positive net removal of arsenic by Cell 5 was significantly better than

occurred in Cells 1 and 2 (mix species), Cell 3 (spike rush), Cell 7 (open-water/duckweed), and Cells 9 and 10 (deepwater plantings of softstem bulrush); no other significant differences in net removal of arsenic were indicated.

Ammonia concentrations in SWRP effluents and CWPP influents, averaged 4.5 mg/l and 6.9 mg/l, respectively (fig. 3). Average concentrations in effluents from wetland cells averaged 4.1 in Cell 5 (3-square bulrush) to 7.2 in Cell 12 (shallow plantings of softstem bulrush), reflecting the anoxic water quality conditions maintained in these cells, as discussed above. Average concentrations in the SWRP effluent and all CWPP effluents exceeded the pending 30-d average low-flow NPDES limit of 1.0 mg/l. Wetland discharge likely could meet permit limits through construction of a direct injection of air or turbulent producing outlet structure or to enhance nitrification and volatilization.

Nitrate plus nitrite concentrations in SWRP effluents and CWPP influents averaged 10.6 and 8.9 mg/l, respectively (fig. 3). Average concentrations in effluents from wetland cells averaged 0.3 and 0.5 mg/l in Cell 3 and 4 (spikerush cells) to 3.3 in Cell 10 (deep plantings of softstem bulrush). Average concentrations in effluents from all wetland treatments cells were less than the pending 30-d average low-flow NPDES limit of 9.0 mg/l.

Total Kjeldahl Nitrogen (TKN) or organic nitrogen in SWRP effluents and CWPP influents in 1997, averaged 9.6 and 8.9 mg/l, respectively (fig. 3). Average concentrations in wetland effluents ranged from 6.7 mg/l in Cell 5 (3-square bulrush) to 9.1 mg/l in Cell 8 (open-water/ duckweed). The NPDES permit contains no limit for TKN.

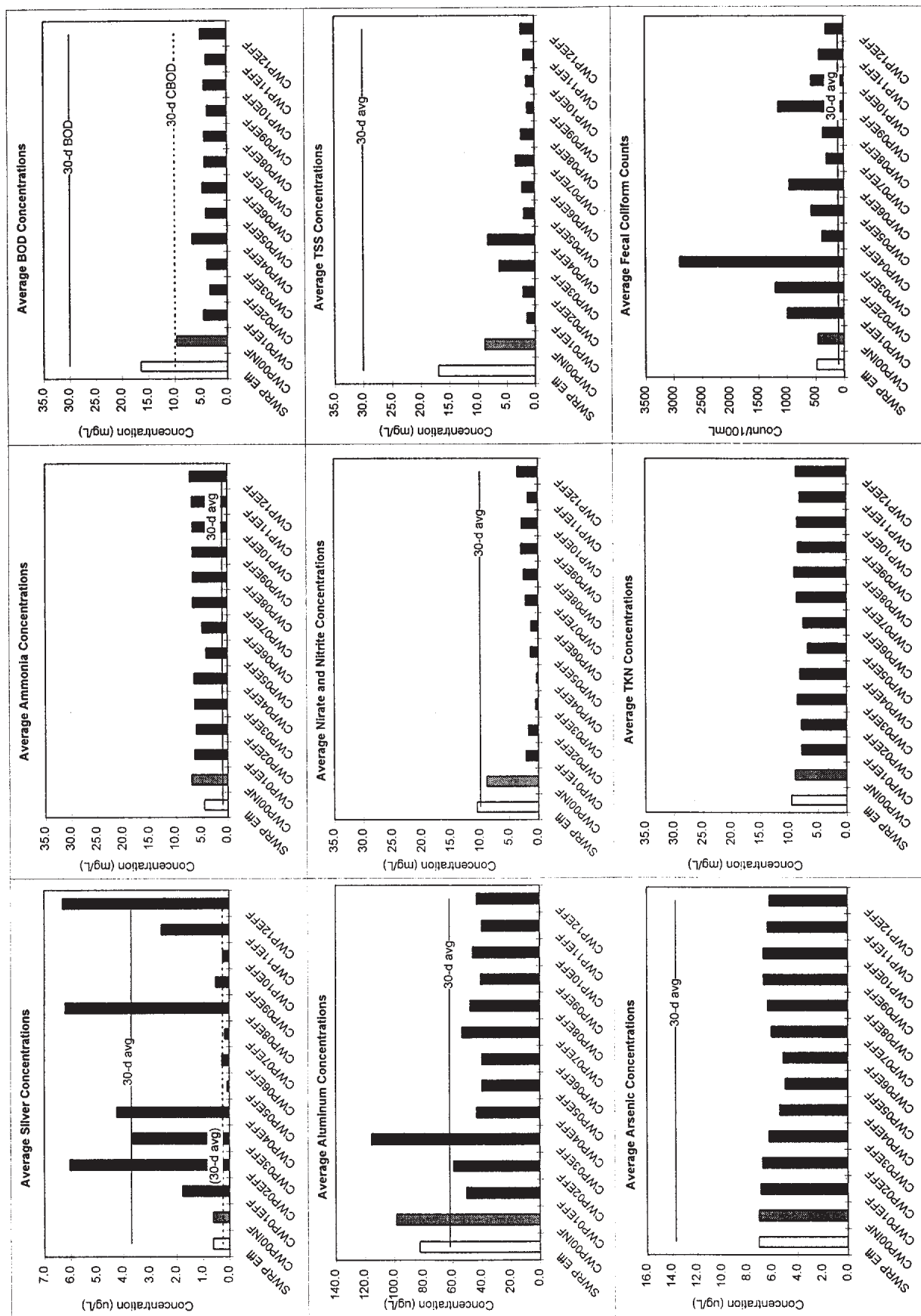


Figure 3—Average Concentrations, March-November 1997, in effluent from SWRP, influent to CWPP, and effluents from CWPP Cells 1-12 (showing present and potential future NPDES discharge permit limits).

Biological Oxygen Demand (BOD) averaged 16.4 mg/l in the SWRP effluent and 9.7 mg/l in the wetland influent (fig. 3). Average concentrations in effluents ranged from 3.3 to 5.1 mg/l for all wetland cells, with the exception of Cell 4, which averaged 6.8 mg/l. The 30-d average BOD under the existing NPDES limits is 30 mg/l; the pending 30-d low-flow CBOD limit is 10 mg/l.

Total Suspended Solids (TSS) during 1997, averaged 17.0 mg/l in the SWRP effluent and 8.9 mg/l in wetland influent (fig. 3). For wetland effluents, average TSS ranged from 1.3 to 3.4 mg/l in all but two wetland cells; average TSS from Cells 3 and 4 (the two spikerush cells) averaged 6.3 and 8.3 mg/l. The present and pending low flow 30-d average NPDES limit for TSS limit is 30 mg/l.

Fecal Coliform averaged 480 counts/100 ml in the SWRP effluent and 460 counts/100 ml in the CWPP influent (fig. 3). Across the CWPP effluents, fecal coliform ranged from 386 counts/100 ml in Cell 4 to 2896 counts/100 ml in Cell 3 (the two spikerush cells). The 30-d average fecal coliform limit under the present NPDES permit is 500 MPN/100 ml and the pending limit is 100 counts/100 ml. For the wetland effluents there were 79 cases where fecal coliform exceeded 100 counts/100 ml.

Fecal streptococci (FS) have been used with fecal coliform (FC) to differentiate human fecal contaminations from that of other warm blooded animals. In editions of *Standard Methods for the Examination of Water and Wastewater* previous to the 17th edition (American Public Health Association 1989), it was suggested that the ratio of fecal coliform to fecal strep could provide information on the source of contamination. A ratio greater than four was thought to indicate human fecal contamination, whereas a ratio of less than 0.7 suggested contamination from non-human sources. In the 19th edition (American Public Health Association 1995), however, the reliability of these ratios is questioned due to poor survival rates for certain fecal strep groups in the environment (which would tend to increase FC/FS ratios) and for other analytical-based reasons (which could decrease these ratios). Consequently, these ratios are no longer considered dependable for use in differentiating between bacterial contamination sources. Nevertheless, lacking another suitable alternative, it may be instructive to note that of the 79 FC exceedances recorded in the wetland effluents, only five effluents held FC/FS ratios greater than four, which may indicate human source contamination. Four of these events occurred during, and the fifth shortly after, the July-August 1997 SWRP upset, which is described in the next section. Of the remaining 74 exceedances, 45 cases (i.e., 60 percent) held FC/FS ratios less than 0.7, potentially indicating non-human bacterial sources.

Variability in analytical results for monitored water quality parameters produced marked differences between corresponding averages for some analyzed water quality parameters in the SWRP effluent and the CWPP influent concentrations, as noted above. These differences may be attributable to unquantified differences due to sampling times, sampling frequency, sample collection or handling, possible wetland piping effects, or other causes. For example, 24-hour composite samples are used to characterize most constituents in the SWRP effluent. In contrast, analyses to characterize CWPP influents and effluents are based on individual grab samples. Despite differences in the sampling approaches used, comparisons between overlapping sampling intervals indicate that the results from the CWPP

influent samples for most analytes are reasonably representative of conditions in the SWRP effluent samples. In turn, analyte results for grab sample collections of CWPP effluents are assumed to be generally representative of the range of potential discharge conditions for the individual wetland cells. Questions remain, however, as to the cause of occasionally high concentration spikes for individual constituents in the CWPP effluents. Specifically, questions exist on whether these concentration spikes would have appeared if composited samples had been used to characterize the CWPP effluents.

Water Quality Benefits of the Wetland During Treatment Failure

During late July and early August 1997, the construction upgrade activities at the SWRP adversely affected the microbial flora in activated sludge treatment tanks, leading to treatment failure. During this period, SWRP effluents were ineffectively treated with multiple and recurring NPDES permit violations for total suspended solids, biological oxygen demand, and fecal coliform. Water quality data collected during this period clearly show the relatively high effectiveness of wetland treatment to buffer downstream receiving waters from many adverse effects during periods of treatment facility failure.

TSS and BOD concentrations that violated NPDES permit limits for the SWRP effluent showed significant improvements after flowing through the CWPP. TSS concentrations detected during this upset in SWRP effluents ranged over 180 mg/l, while effluent from all wetland cells were 19.0 mg/l or less, with most less than 4.0 mg/l; all TSS in all of the CWPP effluents were less than the 30-d average NPDES limit of 30 mg/l for a 76 mgd discharge. BOD concentrations detected in SWRP effluents during this upset ranged over 160 mg/l. Concurrent effluent BODs from all wetland cells ranged between 4 and 16 mg/l, all less than the present 30-d average NPDES limit of 30 mg/l.

Benefits of the CWPP were observed in metals removal through the course of this upset. Silver concentrations detected in SWRP effluent and CWPP influent ranged to 0.51 µg/l, while concentrations of silver in effluents from all wetland cells were at the minimum reporting limit for silver, 0.05 µg/l. Aluminum concentrations detected in the CWPP influent approached 110 µg/l; concentrations in effluents in wetland Cells 5, 6, 8, 9, 10, and 11 (including all wetland vegetation species, except spikerush) were at or near the minimum reporting value for aluminum, 0.40 µg/l. Arsenic concentrations in the SWRP effluent approached 6 µg/l, while concentrations in effluents from the wetland cells range from 3.1 to 4.5 µg/l.

Nitrogen components were generally removed over the course of the treatment plant upset. Ammonia concentrations in SWRP effluents and CWPP influents ranged over 19 mg/l, compared to effluent from wetland Cells 5 and 6 (3-square bulrush cells), where ammonia concentrations were less than 12 mg/l, despite the severely anoxic conditions existing in these cells. Nitrate plus nitrite nitrogen concentrations in SWRP effluents ranged over 3.5 mg/l, compared to average concentrations in all wetland cell effluents of 0.2 mg/l, i.e., the minimum reporting value for these analytes. TKN in SWRP effluents approached 32 mg/l, compared to concentrations between 13 and 16 mg/l found in effluents discharged from six (i.e., 50 percent) of the wetland cells.

Additional Considerations

Assessments of relative evapotranspiration rates (ET), sediment metals accumulations, bioaccumulation of metals, and the economics of wetland development and treatment, have been used to evaluate the effectiveness of wetland operation. Additionally, these evaluations aid in assessing whether to expand on the pilot project technology by constructing a 5-acre or larger demonstration scale, or full-scale treatment wetland.

Relative ET rates were assessed using an independent estimate produced for the City. Potential water loss through wetland evapotranspiration was determined for a 450-acre wetland facility. The assessment revealed that ET could reduce discharge volumes from the SWRP by, perhaps, 1,800 to 2,250 acre-feet/year (i.e., four to five feet of water per year over each acre of wetland).

Sediment metals accumulations were investigated by research cooperators from the USGS BRD. Sediment samples were collected from CWPP cells on February 19, 1997. Concentrations were below or near the minimum reporting values for total silver (<1 mg/kg), aluminum (<2 mg/kg), arsenic (<5 mg/kg), and selenium (<5 mg/kg) in both the inorganic and organic fractions assessed for all samples. Typical environmental sediment concentrations were detected for iron, manganese, mercury, and zinc.

The uptake of metals by organisms is termed *bioaccumulation*. USGS BRD researchers assessed concentrations of silver, aluminum, arsenic, mercury, and selenium in plant stems and roots, and benthic macroinvertebrate tissues collected from CWPP cells and in bryophytes incubated in wetland cells during August 25-28, 1997. Silver was not detectable in any of the tissues. Root concentrations for aluminum, arsenic, and mercury ranged from nearly equal to 10-times or greater than the stem concentrations. Root concentrations for selenium were often less than stem concentrations for the CWPP plants sampled. Greatest root concentration of aluminum, arsenic, and mercury occurred in spikerush, with nearly equivalent concentrations found in the roots of softstem bulrush. Concentrations of aluminum, arsenic, mercury and selenium were generally similar for bryophytes incubated at CWPP cells and the Nature Center (a natural wetland located upstream from the CWPP, which acted as reference samples for this assessment). With individual exceptions, concentrations of these four metals in macroinvertebrates were variable, but generally similar among samples collected from both CWPP and the Nature Center.

An economic evaluation of wetland operation was considered in a 1997 draft benefit-cost analysis from the University of New Mexico (Holmes and Blackwell 1997). The evaluation was conducted for a potential 500-acre treatment wetland facility considered by the City. The analysis gave a benefit-cost ratio of 1.17 for the conservatively short estimated project life of 15 years for a 500-acre constructed wetland facility (typical operational durations projected for constructed wetlands range 20 or more years). Similar analysis and results from other locations reveal that constructed wetland treatment facilities often pay for themselves through cost saving and usage benefits after relatively short periods of operation.

Conclusions and Recommendations

Results from the pilot study offer support for constructing a 5-acre or larger demonstration-scale treatment wetland, which would enable increased realism to evaluate the effectiveness of wetland polishing. These results also support the option to purchase available land and begin construction of a full-scale treatment wetland facility to provide beneficial polishing of Albuquerque wastewater, with concurrent wildlife and recreational benefits. The CWPP results indicate that a wetland treatment system, if constructed using the appropriate wetland plant communities in an appropriately sequenced flow configuration, can produce significant benefits for polishing metals, nitrogen compounds, BOD, and TSS in wastewater discharged by the SWRP. Potential issues related to bacteria and ammonia can be remedied relatively cost effectively.

References

- American Public Health Association, American Water Works Association, Water Environment Federation. 1989. Standard Methods for the Examination of Water and Wastewater, 17th edition. American Public Health Association, Washington, DC.
- American Public Health Association, American Water Works Association, Water Environment Federation. 1995. Standard Methods for the Examination of Water and Wastewater, 19th edition. American Public Health Association, Washington, DC.
- Anonymous. 1997. Constructed Wetlands Treating More of Arizona's Wastewater. Arizona Water Resource 6(1): 1-2.
- Bowen, H. J. M. 1979. Environmental Chemistry of the Elements. Academic Press Inc., New York, NY.
- Constructed Wetlands Study Group Report. 1993. Report to the Bernalillo County Board of County Commissioners, Albuquerque City Council, Mayor of Albuquerque and the Bernalillo County Manager.
- Gearheart, R. A. and M. Higley. 1993. Constructed Open Surface Wetlands: The Water Quality Benefits and Wildlife Benefits—City of Arcata, California. Pages 561-567 in Gerald A. Moshiri (editor). Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Inc., Boca Raton, FL.
- Gelt, Joe. 1997. Constructed Wetlands: Using Human Ingenuity, Natural Processes to Treat Water, Build Habitat. Arroyo 9(4). (<http://phylogeny.arizona.edu/AZWATER/arroyo/094wet.html>).
- Greeley and Hansen. 1996. Economic Evaluation of Alternatives. Section 9 in 91st Avenue Wastewater Treatment Plant Reclaimed Water Study, Phase V - Evaluation of Alternatives.
- Hammer, Donald A. 1989. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural. Lewis Publishers, Inc., Chelsea, MI.
- Holmes, Matthew and Blackwell, Calvin. 1997. A Cost-Benefit Analysis of Albuquerque's Engineered Wetlands.
- Kadlec, Robert H. and Robert L. Knight. 1996. Treatment Wetlands. CRC Press, Inc., Boca Raton, FL.
- Moshiri, Gerald A. (editor). 1993. Constructed Wetlands for Water Quality Improvement. CRC Press, Inc., Boca Raton, FL.
- Mitsch, William J. and James G. Gosselink. 1986. Wetlands. Van Nostrand Reinhold Company Inc., New York, NY.
- Tres Rios Recreation Technical Committee and Phoenix Parks, Recreation and Library Department. 1997. Tres Rios, Arizona: Recreation Component.
- U. S. EPA. 1988. Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment. EPA/625/1-88/022. Center for Environmental Research Information, Cincinnati, OH.

Methods for Increasing Biodiversity in Wetland Creation and Restoration Efforts

Ross Coleman

Abstract—Many wetland creation and restoration projects have successfully restored or created appropriate hydrologic conditions for the support of wetland ecosystems but have not been as successful in establishing a diverse biota of native wetland vegetation. Recent work in the propagation and transplanting of native wetland plant seedlings offers promise for increasing biodiversity while reducing the potential for invasive species to create monotypic stands of low habitat value.

In recent years the values of wetland ecosystems have been recognized on a global scale. Programs have been enacted which encourage or require the creation, enhancement, or restoration of wetland environments. While many wetland projects have been very successful in establishing fully functioning wetland ecosystems, others have met with limited success for a variety of reasons, including low biodiversity of flora resulting from domination by one or more “weedy” species.

Natural Colonization

The traditional approach to wetland vegetation establishment has been something on the order of “build it and they will come”. It has been assumed that by creating appropriate hydrology, the wetland flora will respond. While this method can be successful, especially in the instance where restoration is taking place at the former location of a wetland where extant seed banks are still viable (Dahm and others 1995), frequently the result is less than satisfactory. The natural colonization method gives the practitioner or wetland manager little control over the species composition at the site. One of the most common causes for low diversity of flora in created and restored wetlands is due to the rapid colonization of invasive species, many of which are persistent (Levine and Willard 1990). While some of these species may be locally native, others are either introduced exotics or recent arrivals from another region of the country. Some of the most troublesome species include: the genus *Typha* (cattails - four species occur in the southwest), *Phragmites communis* (common reed), *Phalarus arundinacea* (reed canary grass), *Arundo donax* (giant reed), *Lythrum salicaria* L. (purple loosestrife), and *Sorghum halepense* (Johnsongrass) (Whitson 1996, Corell and Correll 1972). It is not unusual for some of these species to create monotypic stands encompassing many hectares.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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The resulting wetland habitat is compromised with diminished wildlife, recreational, and aesthetic values.

Vegetation Establishment Via Seedlings

Innovations in plant propagation technology and wetland seed germination techniques have provided an alternative method for the establishment of wetland vegetation. Most common emergent macrophytes are now available commercially as container grown seedlings from a number of restoration and native plant nurseries. Some of these nurseries offer custom growing for seed collected near the project site or for rare plant materials. In recent years, wetland projects that have utilized seedling transplants have noted success in preventing or reducing domination by invasive species while increasing the diversity of wetland flora (Ballek 1998). Careful selection of plant materials for site climate, soil and water chemistry, and hydrologic variability is essential. An additional advantage to wetland vegetation establishment from seedlings is the rapid colonization rates from rhizomatous spreading. This is particularly important where soil erosion control is needed. Colonization from existing seed banks (often not present at wetland creation sites) or from intentional seeding can be very slow due to the notoriously low rates of germination for many wetland species (Hammer 1992). The use of genetically adapted container grown seedlings for wetland creation, reclamation, and restoration projects may enhance many of the functional values associated with wetlands. Some of these include: food chain support, sediment control, habitat for fish, shellfish, waterfowl and other wildlife, habitat for rare and endangered species, water quality improvement, education and research, and recreation (National Research Council 1992). Recent regulatory requirements for monitoring of wetland mitigation projects as well as independent research, may provide additional information useful in assessing the value of wetland plantings via containerized seedlings.

References

- Ballek, Len. 1998. Using Container Grown Seedlings, In: Native Plant Highlight Corvallis, MT. 3 p.
- Dahm, Cliff N.; Cummins K.; Valett M.; Coleman R. An Ecosystem View of the Restoration of the Kissimmee River. In: Restoration Ecology, 1995 September, 225-238 Vol. 3.
- Hammer, Donald A. 1992. Creating Freshwater Wetlands. Lewis Publishers Boca Raton. FL 297 p.
- Levine, Daniel A.; Willard D. 1990. Regional Analysis of Fringe wetlands in the Midwest: Creation and Restoration. In: Wetland Creation and Restoration. Kusler and Kentula Ed. Island Press Washington D.C. 594 p.
- National Research Council. 1992. Restoration of Aquatic Ecosystems. National Academy Press, Washington, D.C.

Watershed Issues



Response of Vegetation, Soil Nitrogen, and Sediment Transport to a Prescribed Fire in Semiarid Grasslands

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Abstract—Shrubs and trees have invaded semiarid grasslands throughout much of the Southwestern United States. This invasion not only has decreased grass cover, but also increased runoff and erosion. In fact, sediment from rangelands constitutes the single largest source of nonpoint stream pollutants within the state of New Mexico. Fire, which was a natural factor that shaped and maintained the grasslands, is a management tool that may aid in restoring and maintaining grass cover. However, fire also poses the risk of increasing erosion and further degradation because protection afforded by vegetation is reduced immediately after the fire. Using a randomized block study design, this study measured vegetation cover, soil inorganic nitrogen (N) levels, and erosion amounts associated with the first application of prescribed fire on two semiarid grasslands. The potential for adverse effects from these fires was great because they were performed at the beginning of a drought period. After the first growing season following the fire, grass cover returned to pre-burn levels, and both soil N and erosion amounts were similar to the unburned areas. Thus, prescribed fire for reducing shrub and tree cover may pose minimal adverse risk even under drought conditions.

Fire shaped vegetative communities and played a role in ecosystem dynamics long before the influence of humans. Indeed, it is difficult to find a terrestrial ecosystem that has not been influenced by fire. In North America, lightning-ignited fires shaped prairies and forests (Biswell 1989; Cook 1995; Pyne 1982; Wright and Bailey 1982). Later, Native Americans used fire for hunting, food gathering, and maintaining open savanna-like landscapes, which provided protection against enemy attack (Biswell 1989; Mitchell 1978, Pyne 1982; Wright and Bailey 1982). In the Southwestern United States, widespread fires at 5- to 10-year intervals probably maintained semiarid grasslands (Collins and Wallace 1990; Cook 1995; Gottfried and others 1995; Wright 1980; Wright and Bailey 1982). Past research

has demonstrated that shrubs and trees rapidly invade grasslands in the absence of fire (Briggs and Gibson 1992; Wright 1980).

In semiarid grasslands of the Southwest, shrub and tree invasions occurred following periods of extensive grazing and droughts beginning in the late 1800's and extending to the middle 1900's (Buffington and Herbel 1965). Even without grazing impacts, fire suppression in the mid 1900's created optimum conditions for shrub invasion (Brown 1982), which replaces soil-binding perennial grasses with shrubs such as mesquite (*Prosopis* sp.), juniper (*Juniperus* sp.), burroweed (*Isocoma tenuisecta* Greene), snakeweed (*Gutierrezia sarothrae* (Pursh) Britt. & Rusby), and four-wing saltbush (*Atriplex canescens* (Pursh) Nutt.). Burroweed and snakeweed, in particular, have replaced grasslands on millions of acres in the Southwest (Brown 1982). Concurrent with shrub invasion is an increase in runoff and sediment production from grasslands. In New Mexico, sediment contributions from rangelands (predominantly grasslands) constitute the second leading cause of stream impairment by nonpoint source pollutants (NMWQCC 1994).

Sediment represents a direct degradation of water resources, but it also represents the loss of productivity and soil nutrients. Erosion in the Southwest is episodic in nature, with most soil movement occurring after large, intense storms (Debano 1977). Erosion is initiated by raindrop impaction, which breaks down soil aggregates and suspends clays in surface waters (Brooks and others 1991). Vegetation cover, especially grass cover, reduces raindrop impaction, whereas bare soil promotes runoff and loss of sediment and nutrients. The increase in bare area associated with shrub invasion contributes to increased erosion and runoff from shrub-invaded grasslands (Weltz and Wood 1986). Thus, erosion rates may decline if the grass canopy can be increased and shrubs and bare soils decreased (Brooks and others 1991; Morgan and Rickson 1995).

Drought also is a factor that leads to increased runoff and erosion. Although counter-intuitive, Molles and others (1992) reported increased summer runoff with decreasing winter/spring precipitation in semiarid regions. Thus, periods of high runoff follow periods of winter/spring drought. Mechanisms proposed by Molles and others (1992) to explain this phenomenon include: (1) decreased vegetation and herbaceous cover during drought increases the area subject to raindrop impaction, which leads to increased runoff and sediment transport; (2) an increase in soil hydrophobicity (water-repellency) during drought increases runoff; and (3) the increase in bare soil (and associated solar/albedo relationships) may contribute to generation of

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higher-intensity summer thunderstorms following drought. Davenport and others (IN PRESS 1998) demonstrate how a slight decrease in vegetative cover, which represent areas of sediment removal, can connect areas of bare soil, which greatly increases the “connectiveness” of open spaces and greatly contributes to runoff. Increased runoff has greater energy to carry sediment and erode soils. Periods of soil erosion and arroyo-cutting follow periods of drought because of the strong effects that ground cover has on erosion rates (Wood and others 1987). Cutting of arroyos favors shrubs with deeper root systems that can reach deeper soil moisture.

Perhaps the most cost-effective way of shrub control is through the use of prescribed fire. Fire favors grass growth by killing shrubs (which reduces competition for shallow soil moisture by shrubs), increasing essential nutrients in ash deposition (which is released from litter and burned vegetation), and by increasing light at the soil surface and reducing litter that acts as mulch (Wright 1980). However, in shrub-invaded grasslands, the use of fire faces several potential problems. The lack of fuel continuity may not carry a fire across the landscape, except with high winds that usually exceed those allowed under current burn prescriptions. Also, with very dispersed fuels, cost per unit area increases and the area may require multiple applications of fire to significantly reduce shrub cover. The loss of shrub and grass canopy immediately after a fire increases the potential for soil erosion and nutrient loss. An area treated with prescribed fire remains more susceptible to runoff until the grass canopy can regain and exceed pre-burn coverage. The combination of an increase in available nutrients and reduced vegetation cover creates the possibility for loss of nutrient and soil resources (Baker 1990; Vitousek and Howarth 1991).

The effects of fire can range along a gradient from minimal to extreme, dependent upon the interaction of a variety of conditions. To evaluate the effects of fire in semiarid grasslands, we constructed conceptual models that identified potential patterns of response in a number of variables based upon fire intensity or time since burning. A major factor determining the magnitude of response is the fuel load and its continuity, which are factors that contribute to fire “intensity” (total energy released per unit area). If fuels are sparse and/or widely separated, then fires will not carry across the landscape and the effects would be minimal at the landscape scale, but important to small areas (individual plant scale). Sparse fuels with high fuel continuity may carry a fire across the landscape, which will increase its spatial coverage, but will still have low “intensity” (relatively low maximum temperature, short residence times, and shorter flame lengths). If fuels are high and relatively continuous, then both coverage and intensity will increase.

Fire consumes above-ground vegetation, so vegetation cover will show an immediate decline following fire. However, nitrogen (N) mineralized during combustion of organic matter is expected to promote grass growth. Grass cover may return to or actually exceed undisturbed conditions due to reduction of litter, increased sunlight, and increased available nutrients. This would likely continue until the buildup of litter slows nutrient cycling or allows fire to progress through the system once more.

The immediate release of available N by fire is well documented in nearly all vegetation types, but there is little

information on the effects of fire in semiarid grasslands on potentially mineralizable N, upon which future productivity relies. The overall goal of management with prescribed fire is to increase the rate of N turnover thereby favoring vegetation that responds quickly to fire, particularly grasses and forbs.

The objectives of this research were to determine the effects of prescribed fire in two semiarid grasslands on vegetation cover-type (bare, grass, or shrub), potentially mineralizable N (as a measure of site fertility) and soil erosion. Specific hypotheses included: (1) after an initial decline in vegetation cover, grasses should respond more rapidly than shrubs and achieve greater cover relative to shrubs; (2) N in ash should increase the amount of mineralizable N following the fire, but mineralizable N should return to that of control or unburned soils following regrowth of vegetation; and (3) high intensity precipitation should increase erosion following burning until the vegetation cover recovers, which would then lead to a decline in erosion. This article presents the 1-year results of the first in what is expected to be many prescribed fires directed at decreasing shrub invasion into semiarid grasslands in central New Mexico.

Methods

Site Description

The research is conducted at two study sites near Albuquerque, New Mexico. The West Mesa site is west of the City on Open Space property (fig. 1), and the Bernalillo Watershed is north of the City on Cibola National Forest property (fig. 1). The elevation of the West Mesa site is about 1820 m and the Bernalillo Watershed is about 1660 m. The West Mesa soil is a fine sandy loam and the Bernalillo Watershed soil is a clayey loam (CS White, unpublished data, 1996). The West Mesa grassland represents a Great Basin Desert Scrub/Desert Grassland ecotone, and the Bernalillo Watershed represents a Plains-Mesa Grassland/Desert Grassland ecotone (Brown 1982). Dominant perennial grasses on the Bernalillo Watershed were: black, blue, and sideoats grama (*Bouteloua eriopoda* (Torr.) Torr., *B. gracilis* (Willd. ex Kunth) Lag. ex Griffiths, *B. curtipendula* (Michx.) Torr.), respectively); purple threeawn (*Aristida purpurea* Nutt.); galleta (*Hilaria jamesii* (Torr.) Benth); and dropseed (*Sporobolus* sp.). Dominant perennial grasses on the West Mesa were: Indian ricegrass (*Oryzopsis hymenoides* (Roem & Schult.) Ricker); needle-and-thread grass (*Stipa comata* (Trin. & Rupr.); purple threeawn; galleta; black grama; and dropseed. Annual precipitation for both sites averages about 20 to 25 cm; however, precipitation measured at the Albuquerque station of the U.S. Weather Bureau during the study period was considerably less than the monthly mean of the previous 40 years (fig. 2a). A precipitation deficit began during the beginning of 1995 and lasted through the first 5 months of 1996, after which slightly higher than normal precipitation occurred through the rest of 1996 (fig. 2b).

Both sites were removed from livestock grazing; the animals were removed in 1947 from the Bernalillo Watershed and in the early 1970's from the West Mesa. Despite the removal of grazing, each site had a substantial shrub component, particularly broom snakeweed. The Bernalillo

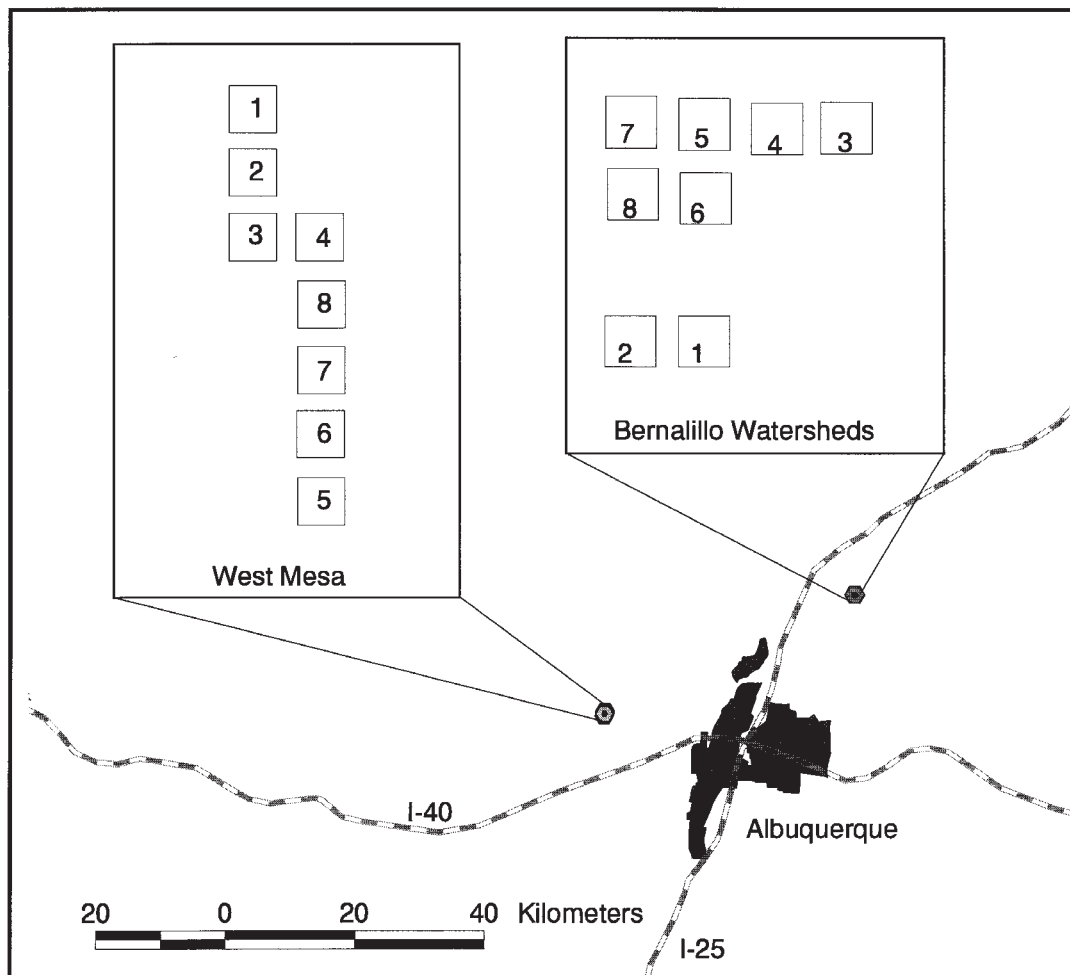


Figure 1—Map showing the general locations of the Bernalillo Watershed and West Mesa research sites located near Albuquerque, NM.

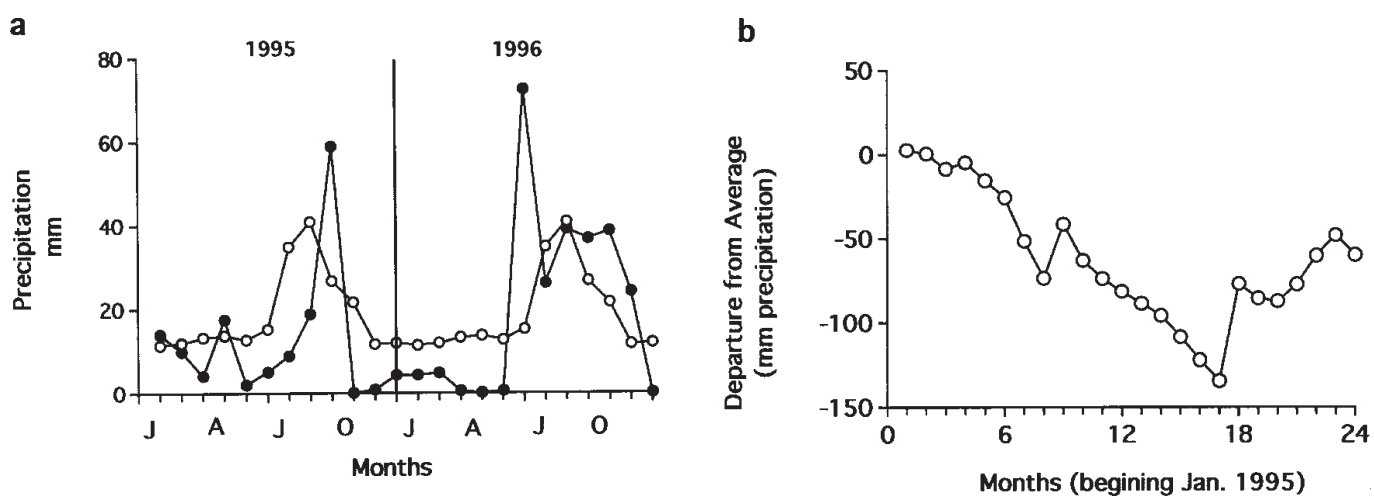


Figure 2—Monthly mean precipitation for the Abq weather station for the period since 1960 (open), and monthly precipitation (solid) during 1995 and 1996 (a), and cumulative departure curve from the long-term mean precipitation volumes beginning in 1995 through 1996 (b).

Watershed had extensive flood and erosion control features constructed by the Soil Conservation Service and the Forest Service in the 1950's, including steep-slope terraces, furrow plowing, pitting, check dams and grass seeding. These efforts followed severe flooding and erosion that blocked the main north-south highway with sediment in 1954, which occurred during a period of record-setting region-wide drought (Betancourt and others 1993).

Experimental Design

Each site includes eight plots; four control and four burned, which were arranged in a randomized block design. At the Bernalillo Watershed site, six plots (3 pairs of treatment and control) are located on one mesa, while the other two (1 treatment and 1 control) are located on a mesa to the south (fig. 1). On the West Mesa, plots were arranged in a near linear fashion below the ridge-line. At both sites, each plot is 1 ha (100 m on a side) with at least 30 m separating the plots on all sides. Soil and vegetation sampling took place within a 60 m by 60 m area within the 1 ha plot to protect against edge effects (fig. 3). Within each plot, three permanently marked 60-m lines were used for vegetation cover and density measurements. Soils were collected by cover-type (shrub, grass, or bare soil) along three adjacent 60-m lines. In the Bernalillo Watershed, each plot had two 3 x 10 m runoff-erosion collectors, while the West Mesa had only one collector per plot (to minimize potential disturbance to archeological resources).

Prescribed Fire

The Bernalillo Watershed was treated with prescribed fire November 15-16, 1995, with a total of about 168 ha burned. The experimental plots were contained within the burn area. The control plots were protected by fire retardant foam applied around their perimeters. Weather conditions were favorable for prescribed burning with warm temperatures for the season (about 55 °F), moderate relative humidity, and light winds. However, the fuels in the Bernalillo Watershed were discontinuous, which resulted in patchy coverage by the fire.

The West Mesa site was treated with prescribed fire February 14, 1996. At this site, only the treatment plots were burned. Again, weather conditions were favorable for prescribed burning with warm temperatures for the season, moderate relative humidity, and light but steady winds. Fuels were more continuous at this site and the grasses were of taller stature, which allowed for nearly complete burn coverage with only small patches that did not burn. The plots were blacklined on three sides, then lit across the top and the fire moved with the wind across the entire plot, leaving only a few patches unburned.

Measurements

Vegetation Community Structure—Aboveground cover of individual plant species, as well as non-vegetation ground cover by categories (bare soil, litter, gravel and rock), were measured using the Community Structure Analysis technique (Pase 1981, Wolters and others 1996). Each of the three 60-m vegetation transects within each plot were

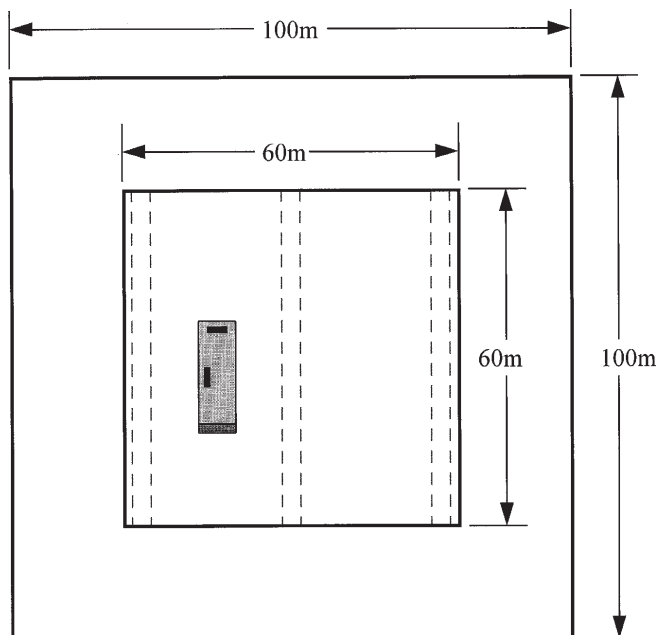


Figure 3—Design of experimental plots showing the interior 60 m by 60 m area actually sampled, the soil and vegetation transects (dashed lines) and the relative placement of the runoff collector (rectangular shaded area in plot). Erosion bridges were installed about 30 cm from the border of the runoff collector centered along the top and one side of the collector (darker shaded areas). Rain gutter with galvanized sheet metal lip that drained into a 20 l bucket was installed at the bottom of the collector.

measured. These transects were measured before the prescribed fire, soon after the prescribed fire, and after the first growing season after the fire.

Soil Measurements and Analyses—Soil samples were collected three times at both sites; before the prescribed fire, shortly after the prescribed fire, and after the first growing season after the fire. Surface soil samples were collected under three cover-types (shrub, grass, and bare soil) by taking 4-cm wide cores to a depth of 20 cm at two locations along three 60-m belt transects inside the sampling area. The six soil cores of each cover type from each plot were composited into a single sample. This sample design produced one composite sample from each plot for bare, grass, and shrub cover-types (sample-size of four for treatment and control).

Samples were transported on ice to the University of New Mexico, where they were sieved (2 mm), mixed, and stored at 5 °C for further analyses. After determining water-holding capacity (WHC) (White and McDonnell 1988), a portion of each sample was adjusted to 50 percent of determined WHC and up to 11 subsamples were apportioned into plastic cups. Each cup contained approximately 30 g dry-weight mineral soil. One subsample of each sample was immediately extracted with 100 ml 2 N KCl for NH_4^+ -N and NO_3^- -N analyses. The remainder of the cups were covered with plastic wrap, sealed with a rubber band, and incubated in the dark at 20 °C. The plastic wrap minimized water loss

during incubation, yet exchange of CO_2 and O_2 was sufficient to keep the subsamples aerobic during incubation. Moisture content was monitored by mass loss and replenished as needed. At weekly intervals, one subsample of each sample was removed and extracted with KCl for 18–24 h. The clarified KCl was filtered through a Kimwipe® and analyzed for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N} + \text{NO}_2^-\text{-N}$ on a Technicon Auto-Analyzer (Technicon, Tarrytown, NY) as described in White (1986). Mineralizable N was equal to the maximal amount of inorganic N (sum of ammonium and nitrate) produced during incubation by each soil.

Water content of the composited sample was measured gravimetrically after 24-h desiccation at 105 °C. Soil texture was measured by the hydrometer method (Day 1965). These sampling and analysis methods allowed for the determination of soil characteristics by cover-type.

Sediment Yield—Runoff-sediment collectors were designed after those used by the Water Erosion Prediction Project (WEPP; USDA, 1196 Building SOIL, Purdue University, West Lafayette, Indiana 47907-1196). Size and placement of the collectors at the West Mesa site were negotiated with and approved by Albuquerque Open Space archaeologists to minimize soil disturbance and damage to articles of archeological value. Following site approval by the State Historic Preservation Office, one collector per plot was installed at the West Mesa site. Two collectors per site were installed at the Bernalillo Watershed. All collectors were constructed by installing galvanized flashing around the perimeter of the 3 m by 10 m runoff collection area after the fire treatment (fig. 3). Along the bottom 3-m side, a plastic raingutter with galvanized flashing was installed at ground level to collect runoff and sediment. At the end

of the gutter, a hole was dug and a 20-l bucket was placed in the hole and attached to the end-cap on the gutter by a section of garden hose. Both sediment in the gutter and bucket were collected at periodic intervals. This experimental design resulted in four treatment and four control sediment samples for each collection at the West Mesa site, and eight treatment and control sediment samples at the Bernalillo Watershed (two collectors in four plots).

Soil Erosion Bridge—Change in soil microtopography within each runoff collector was monitored using two soil erosion bridges (one parallel to the top and one along the side of each collector; fig. 3) established within the collectors prior to the burn. A soil erosion bridge measures small-scale changes in soil microtopography (Shakesby 1993; Wilcox and others 1994). The purpose of the bridge is to accurately determine net soil gain or loss. Following a burn, contraction and expansion of vegetation could coincide with movement of soil from bare areas to vegetated areas. Movement of soil at this scale could result in a simple redistribution of soil with no net gain or loss. Similar to the pattern described by Watt (1947), the soil surface may rise as individual plants become established and mature (termed a building phase), and then degenerates upon plant mortality, but the area as whole could remain in equilibrium with simple redistribution of materials within the area. Soil bridges were utilized to measure changes in soil microtopography to provide an accurate measure of net soil movement.

The actual bridge is constructed from an aluminum bar (35 mm square), 1.5 m in length, with 31 holes machined and fitted with brass bushings at 5 cm intervals (fig. 4). The bridge is situated on two permanent rebar stakes, leveled

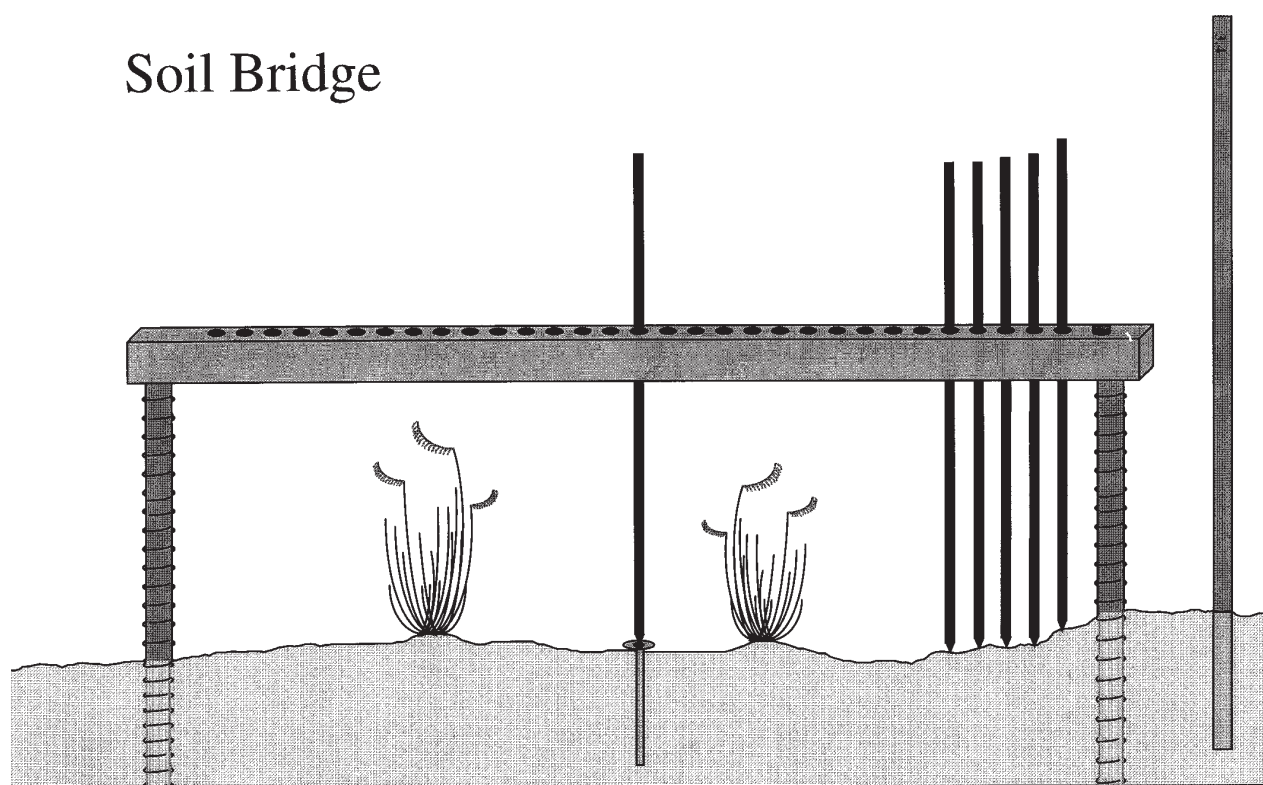


Figure 4—Schematic drawing of soil erosion bridge showing end rebar, center nail at soil surface, and 5 measuring pins.

with the help of a bubble level on the bridge, and secured with wood shims to prevent movement of the bridge. To increase the accuracy of this method, a spike with a dimple in the head is driven into the ground below the center pin. An aluminum pin is then inserted through the bridge and into the dimple in the head of the nail. The end rebar stakes and the center nail create a three point line, which increases the accuracy over what would normally be a two point line (Shakesby 1993; Wilcox and others 1994). Once the bridge is secured, pins are inserted through holes in the bridge to the soil surface and the portion of each pin extending above the bar is measured. The 30-point profile reflects the soil surface topography. When measured over time, these measurements document minor changes in soil surface dynamics and net gain or loss in soil resources. The soil erosion bridges were measured before the fire, immediately after the fire, in July 1996 after the summer rains began, and after the first growing season after the prescribed fire.

Statistical Analyses

Each site (Bernalillo and West Mesa) was analyzed separately. Effect of prescribed fire on soil potentially mineralizable N was analyzed using Analysis of Variance (ANOVA) procedures in SAS (SAS Institute Inc., Cary, NC). Soil bridge measurements and sediment transport were analyzed using repeated measures ANOVA procedures in SAS, which generated an analysis for the treatment, collection, and their interaction factors. Effect of the prescribed fire on vegetation cover was determined using the GLM repeated measures procedure on SPSS (v7.5, citation). Unless otherwise indicated, a significance level of $P \leq 0.05$ was used.

Results

Bernalillo Watershed

Vegetation Cover—Vegetation cover both before and after the prescribed fire was relatively sparse and patchy, which lead to high within-treatment variances for all collections. Cover of total vegetation, grass, and shrubs was the highest in the collection before the fire treatment (fig. 5), which was near the beginning of below-normal precipitation in the region (fig. 2). All cover-types declined on treatment and control plots in the second collection, after the prescribed fire. Total vegetation and grass cover increased in the third collection to near that of the first collection; however, shrub cover continued to decline in both the control and treatment plots. For total vegetation cover, grass cover, and shrub cover, treatment was not a significant factor, nor was the time $\times$ treatment interaction. The time factor was significant for the change in vegetation for both time intervals (change from collection 1 to 2 ($P = 0.001$), and from collection 2 to 3 ($P = 0.038$)).

Mineralizable N—Extractable inorganic N (sum of ammonium and nitrate) showed a general linear increase throughout the 70-d incubation period for soils from all cover-types (shrub, grass, and bare) from the Bernalillo Watershed and the West Mesa sites. Thus, the sum of ammonium and nitrate in the 70-d extraction equalled mineralizable N in most soils. In soils from the Bernalillo

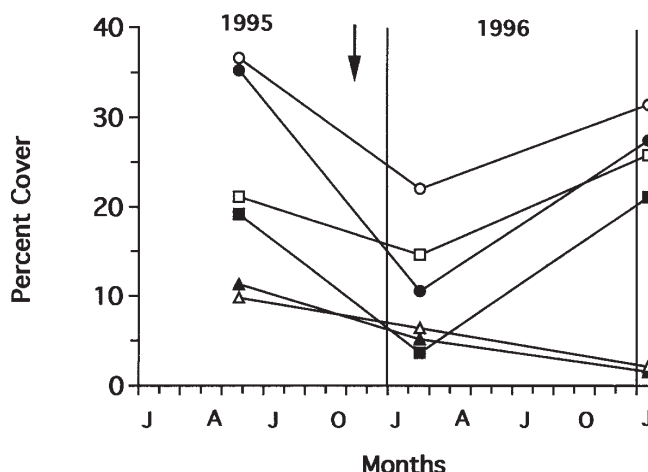


Figure 5—Changes in vegetation cover (circles, total cover; squares, grass cover; triangles, shrub cover) on the control (open symbols) and burned (filled symbols) plots at the Bernalillo Watershed. Arrow indicates when the prescribed burn occurred.

Watershed, mineralizable N is greatest in soils under shrub, slightly lower in soils under grass, and lowest in bare soils (fig. 6) for all collections. The fire treatment and the interaction of fire and collection were not significant factors ($P > 0.05$) on mineralizable N levels, but time of collection was highly significant ($P = 0.003$). The effect of collection is shown by both the treatment and control samples increasing after fire and then decreasing on the last collection (fig. 6).

Erosion—The amount of sediment transported from each collector was highly variable following the fire in both treatment and control plots (fig. 7). Although the means of

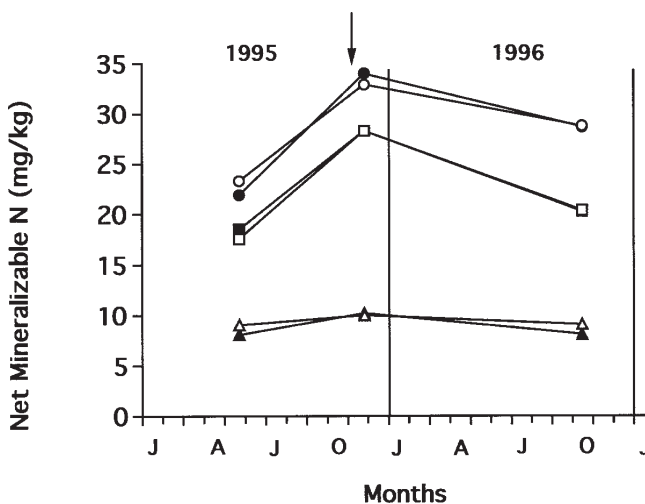


Figure 6—Changes in mineralizable N content of soils beneath different vegetation cover-types (circles, shrub; squares, grass; triangles, bare soil) on the control (open symbols) and burned (filled symbols) plots at the Bernalillo Watershed. Arrow indicates when the prescribed burn occurred.

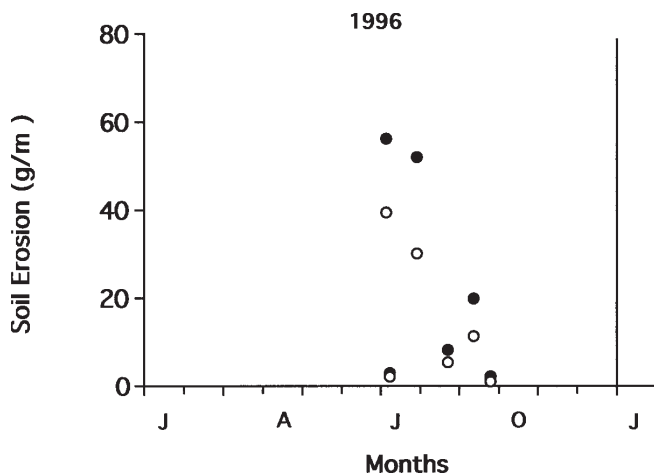


Figure 7—Amount of soil trapped in the gutters at the bottom of the runoff collectors in the control (open circles) and burned (filled circles) plots for six different collections during 1996 at the Bernalillo Watershed. The first runoff events occurred in late June and early July, 1996.

the treatment plots were consistently higher than the means of the controls, there was no significant effect of the treatment factor ($P = 0.102$) on sediment transport, which in part was due to the high within-treatment variance. Collection was a highly significant factor ($P < 0.001$), while the treatment $\times$ collection interaction factor was near significant ($P = 0.052$). In general, the relative difference between the treatment and controls diminished during the course of the first year, which would be consistent with a relatively greater increase in cover on burned plots in response to the precipitation from June 1996 through the end of the year with a corresponding increase in site stability following plot establishment.

Soil Erosion Bridges—The repeated measures ANOVA identified that treatment, collection, and their interaction were all significant factors ($P = 0.038$, $P = 0.001$, and $P = 0.045$; respectively) for the change in soil microtopography in the Bernalillo Watershed. Both treatment and control soils show a decline in soil surface (representing net erosion) during the course of the study, except for the control plots which showed no change or a net gain for the last collection (fig. 8). The rate of loss appears greater in the treatment than in the control plots.

West Mesa

Vegetation Cover—Vegetation cover was relatively uniform across the plots and the grasses were taller than at the Bernalillo Watershed, which led to much more uniform coverage by the prescribed fire treatment. Initially, total cover, grass cover, and shrub cover were similar between the treatment and control plots (fig. 9); however, all three cover types were significantly reduced following the prescribed fire while cover by these types on the control plots was unchanged. Following the first growing season after the fire, grass cover on the burned plots increased 19.5

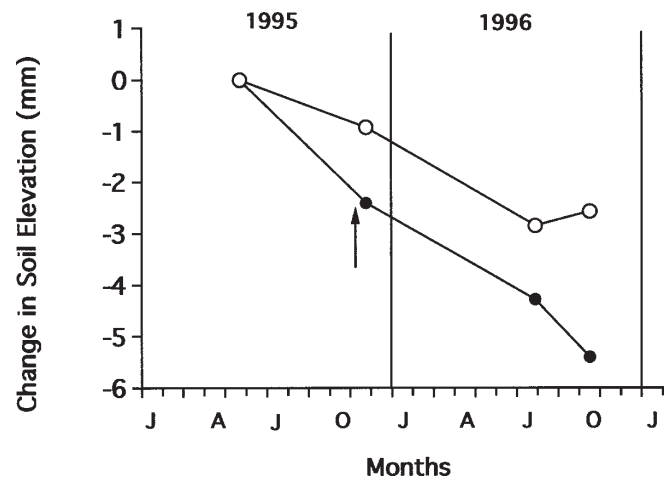


Figure 8—Net change in the soil surface measured below the erosion bridges within the control (circles) and burned (filled circles) plots at the Bernalillo Watershed. Arrow indicates when the prescribed burn occurred.

percent (from 0.7 percent cover to 20.2 percent), while grass cover on the control plots increased by 4.7 percent (from 21.1 to 25.8 percent, which was not a significant increase). Shrub cover was significantly reduced on the burned plots after the fire and did not increase by the third collection. Shrub cover in the control plots was not significantly different after the fire, but declined between the second and third collection. For total vegetation cover, grass cover, and shrub cover, treatment and the time $\times$ treatment interaction factors were significant ($P < 0.05$).

Mineralizable N—Mineralizable N was highest in soils under shrub, intermediate under grass, and lowest in bare

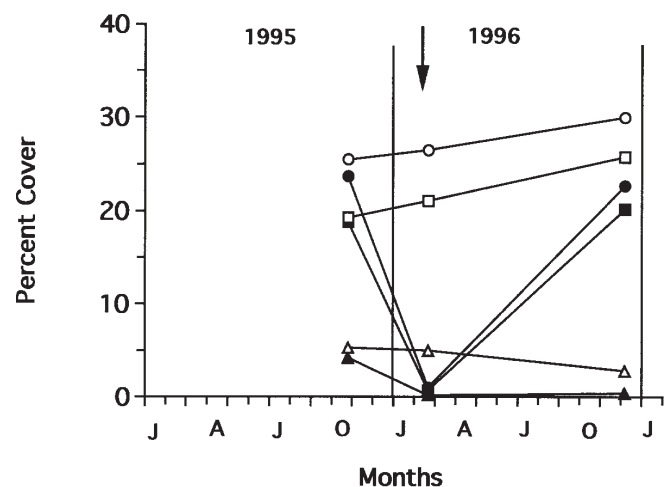


Figure 9—Changes in vegetation cover (circles, total cover; squares, grass cover; triangles, shrub cover) on the control (open symbols) and burned (filled symbols) plots at the West Mesa. Arrow indicates when the prescribed burn occurred.

soils (fig. 10). The repeated measures ANOVA identified collection to be the only significant factor ($P < 0.001$) for mineralizable N in soils of the West Mesa. Mineralizable N increased in all soil-types following the prescribed fire in both treatment and control plots, except for the soils under grass in the control plots. All soils showed a particularly sharp decline in mineralizable N following the summer growth in both the control and burned plots.

Erosion—Treatment, collection, and their interaction were not significant factors for soil erosion at the West Mesa site. Variance was very high in all collections in both the treatment and control plots. The high variance and small sample size (four plots per treatment) resulted in no significant differences between treatment and control plots (fig. 11), but the means of the treatment plots were higher than the mean of the control plots in all collections.

Soil Erosion Bridges—The treatment plots showed a net rise in the soil surface immediately after the prescribed burn, but the soil surface degraded to below the initial level in both subsequent collections (fig. 12). The control plots showed no significant change during the study period. The only significant difference between the treatment and control plots occurred in the immediate post-treatment collection.

Discussion

To say that the weather conditions before and after the prescribed fires were less than optimal would be an understatement. As with most management activities, an extensive planning and budget process preceded the actual prescribed fires. The original study plan targeted a late September-October prescribed fire at both sites, a period when the days are still warm with breezes, but not high winds, and maximum fine fuel in response to summer rains.

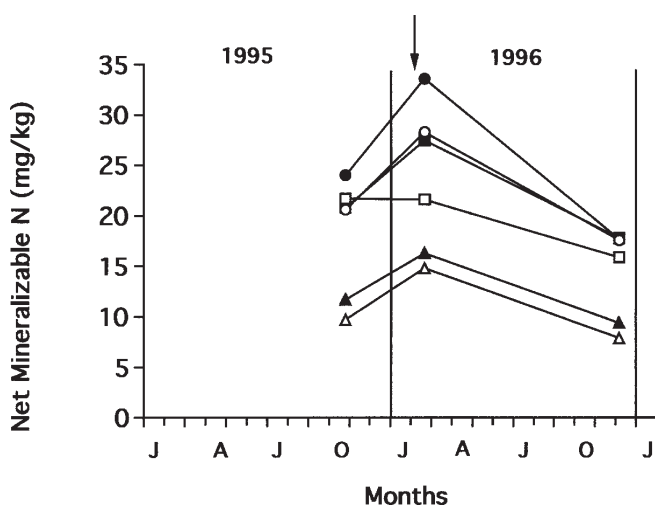


Figure 10—Changes in mineralizable N content of soils beneath different vegetation cover-types (circles, shrub; squares, grass; triangles, bare soil) on the control (open symbols) and burned (filled symbols) plots at the West Mesa. Arrow indicates when the prescribed burn occurred.

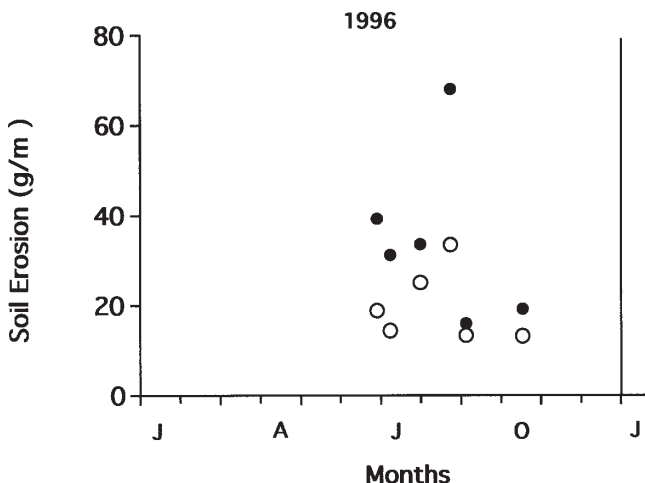


Figure 11—Amount of soil trapped in the gutters at the bottom of the runoff collectors in the control (open circles) and burned (filled circles) plots for six different collections during 1996 at the West Mesa. The first runoff events occurred in late June and early July, 1996.

Instead, the drought that started at the beginning of 1995 continued through the summer, providing little new growth. In September the rains exceeded the long-term average (fig. 2b), which forced a delay until November for the Bernalillo Watershed and February for the West Mesa. Optimally, ash produced by the fire would have leached into the soil with the light rains expected at that time of year. However, precipitation continued below normal through the winter and winds blew ash off the burned plots, which was evident from the ash trapped by vegetation in the unburned plots. In the Bernalillo Watershed, this was particularly important because the control plots were “islands” within the

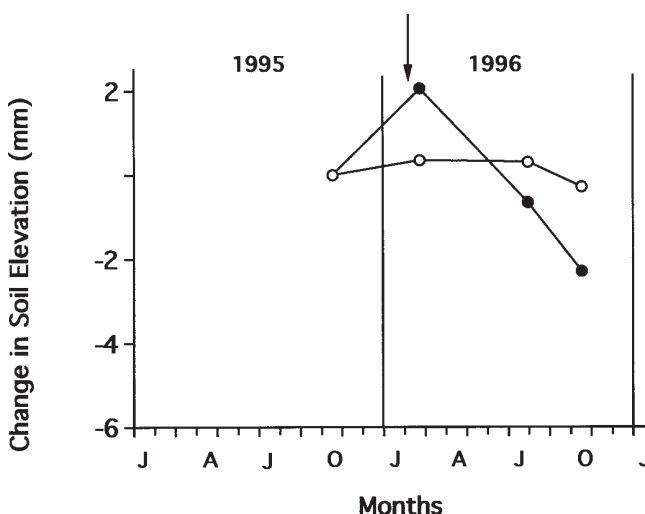


Figure 12—Net change in the soil surface measured below the erosion bridges within the control (circles) and burned (filled circles) plots at the West Mesa. Arrow indicates when the prescribed burn occurred.

treated area and could receive ash from all sides. In contrast, the treatment plots were "islands" within the sea of unburned grasslands at the West Mesa site, so potential ash contribution was less than at the Bernalillo Watershed. Rains finally came in June of 1996, but they were high intensity thundershowers that generated runoff and soil erosion, even on the control plots where vegetation was not consumed by fire. Thus, the full benefit of nutrients in the ash was not expressed at the treatment plots, and the control plots benefitted from ash blown from the treatment plots.

For the collection after the fire, vegetation cover in the control plots was less than before the fire, which in part could have been caused by the persistent drought conditions preceding the prescribed fire. However, trespass animals on the site consumed an unknown amount of vegetation and could be the cause of the observed decline. Perhaps the best evidence of the drought was the persistent decline of shrub cover throughout the first year of study. The decline may indicate that shrubs are more susceptible to winter/spring drought, which is the period when soil moisture at greater depth is usually replenished. At both sites, grass cover in both treatment and control plots increased in the final collection while the shrubs showed no change or a decline. Thus, the desired change in greater cover by grass relative to shrubs occurred on both sites, but the change cannot be attributed to fire alone because of the continued decline in shrubs in the control plots at both sites.

Contribution of ash to the control plots may account for the lack of an expected treatment effect in the soils of the burned plots for mineralizable N. However, mineralizable N also increased in the soils beneath shrubs and bare soils in the control plots on the West Mesa after the prescribed fire. This increase suggests that factors other than ash may contribute to the mineralizable N pool in the soils over the period between the pre- and post-burn soils. Possible explanations for the increase in mineralizable N could be the contribution of readily mineralizable N following mortality of microbial or root biomass during the drought period between the initial and post-fire soil collections.

The decline in mineralizable N content of soils in all plots at both sites between the second and third collection coincides with the increase in grass cover, which suggests that the available N pool may be sequestered in current growth. If precipitation remains above normal and available N is not replenished before the next growing season, then the decline in mineralizable N suggests that net primary production may be limited by available N supply during the next growing season.

The patterns of soil loss, although not statistically significant in most cases, were consistent with our expectations. Reduction in vegetation cover was expected to temporarily increase potential soil erosion, and the treatment plots at both sites had consistently higher (but not significantly different) soil loss than the control plots (fig. 7 and 11). As vegetation cover increased following the summer rains, erosion tended to decrease on both the treatment and control plots at both sites. It is possible that storm intensity also decreased over the summer, which could, in part, account for the apparent decline in erosion. This pattern of declining erosion as the summer runoff season advanced was also shown by Wilcox (1994) at another location in New Mexico, and Yair and others (1980) observed similar declines in sediment concentrations with repeated runoff events in arid regions of the northern Negev.

The soil bridges were installed on the sites before the prescribed fires and before the flashing was installed around the erosion collectors. The second bridge measurements reflect the combined effects of soil loss between the two collections, disturbance from installation of the flashing, soil compaction from footsteps by personnel during the prescribed fire, and trespass livestock at the Bernalillo Watershed. Between the second and third sampling period, both wind and water erosion could have contributed to the soil loss seen at both sites. Rain splash and water erosion probably were the major factors contributing to change between the third and fourth collection, as evident from the soil splashed onto the flashing between these collections (personal observation). If the trend in increasing vegetation cover continues, the soil surface is expected to stabilize, or perhaps even show a net increase if the vegetation traps enough particles and reduces compaction from rainsplash.

The soil bridges appear to over-estimate the rate of soil erosion as seen in the runoff plot as a whole. When the total mass lost during the study period from the erosion plots is evenly distributed over the entire plot, the control and treatment plots had an average loss of 0.09 mm and 0.14 mm, respectively, on the Bernalillo Watershed, and 0.12 mm and 0.2 mm, respectively, on the West Mesa. The soil bridges indicate greater loss (1.0 mm and more) from all plots, except the control plots on the West Mesa (fig. 8 and 12). Since the bridges were installed along the top and one side of the erosion plots, it is possible that soil loss from those positions is greater than from the plot as a whole.

Conclusions

Hypothesis 1: after an initial decline in vegetation cover, grasses should respond more rapidly than shrubs and achieve greater cover relative to shrubs. This occurred on both grasslands, but cannot be attributed to fire alone.

Hypothesis 2: N in ash should increase the amount of mineralizable N following the fire, but mineralizable N should return to that of control or unburned soils following regrowth of vegetation. This pattern did not occur, in that mineralizable N in both treatment and control soils rose after the fire and declined following the summer growing period.

Hypothesis 3: high intensity precipitation should increase erosion following burning until the vegetation cover recovers, which would then lead to a decline in erosion. Although not desired, this occurred at both grasslands with an apparent decline in erosion as the summer progressed. However, we can only assume the decline in erosion was due to increased vegetation cover because the contribution from other factors is unknown.

The results of this study are noteworthy for two reasons. First, the weather preceding and following the treatment with prescribed fire was very dry. This drought period lasted until early summer. The subsequent thunderstorms were frequent and heavy. Thus, it was expected that runoff and sediment yields and nutrient loss would be significantly greater from burn plots as compared to control plots. Surprisingly, this did not occur with regularity. Second, shrub cover was reduced and remained low relative to grass cover after the fire at the West Mesa site, but not different from

the controls at the Bernalillo site. Research from other semiarid grasslands suggest that stimulation of grass growth occurs for up to four years following fires in these systems (Bock and Bock 1990; Pase and Granfelt 1977). Grass cover in the burn plots would have to continue to increase without an increase in shrubs for the management objective to be met following the first fire. It was anticipated that many fires may be required to obtain the desired objective. Future management will require continued treatment with fire to maintain the grassland in proper functioning condition.

Acknowledgments

This work was supported by grants from the National Science Foundation (No. BSR-88-11906 and DEB-9411976) and by the Rocky Mountain Research Station. Gratitude is extended to all the people who helped in this research: Richard Gatewood, Ruben Leal, Randi Paris, John Craig, Chris Thomas, Bill Hauck, Robyn Phillips, Ray Romero, Wendy Jones Brunnemann (City of ABQ Open Space), and all the people who actually performed the prescribed burn (Cibola National Forest - Sandia Ranger District, State Forestry, Placitas Fire Brigade, Sandoval County Fire Department, New Mexico Forestry and Resources Conservation). This research is aided by a grant from the Cibola National Forest. Further funding was obtained for the support of Steve Hofstad from the University of New Mexico through the Research Project and Travel Grant, the Student Research Allocation Committee, and the Vice President's Research Fund provided by the Office of Research. This is Sevilleta Long-term Ecological Research Program Pub. #116.

References

- Biswell, H. H. 1989. Prescribed Burning in California Wildlands Vegetation Management. University of California Press. Los Angeles, CA.
- Baker, M. B. 1990. Hydrologic and Water Quality Effects of Fire. p. 31-42 IN: J.S. Krammes (tech. coord.). Effects of Fire Management of Southwestern Natural Resources Symposium. Gen. Tech. Rep. RM-191. USDA Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Betancourt, J. L., E. A. Pierson, K. A. Rylander, J. A. Fairchild-Parks, and J. S. Dean. 1993. Influence of history and climate on New Mexico piñon-juniper woodlands. p. 42-62 IN: E. F. Aldon, and D. W. Shaw (tech. coords.) Managing Piñon-Juniper Ecosystems for Sustainability and Social Needs: proceedings of the symposium April 26-30, 1993 ; Santa Fe, New Mexico. Gen. Tech. Rep. RM-236. USDA Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Bock, C. E. and J. H. Bock. 1990. Effects of Fire on Wildlife in Southwestern Lowland Habitats. p. 50-64 IN: J.S. Krammes (tech. coord.). Effects of Fire Management of Southwestern Natural Resources Symposium. Gen. Tech. Rep. RM-191. USDA Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Briggs, J. M., D. J. Gibson. 1992. Effect of Fire on Tree Spatial Patterns in a Tallgrass Prairie Landscape. Bulletin of the Torrey Botanical Club. 199(3):300-307.
- Brooks, K. N., P. F. Ffolliott, H. M. Gregersen, and J. L. Thames. 1991. Hydrology and the Management of Watersheds. Iowa State University Press. Ames, IA.
- Brown, D.E. (ed.) 1982. Biotic Communities of the American Southwest-United States and Mexico. Desert Plants 4(1-4).
- Buffington, L. C. and C. H. Herbel. 1965. Vegetation changes on a semidesert grassland range from 1858 to 1963. Ecological Monographs 35:139-164.
- Collins, S. L., and L. L. Wallace Eds. 1990. Fire in North American Tallgrass Prairies. University of Oklahoma Press. Norman, OK.
- Cook, K. 1995. Prescribed Fires Benefit Carson National Forest. New Mexico Wildlife. July/August 1995: 10-13.
- Davenport, D. W., D. D. Breshears, B. P. Wilcox, and C. D. Allen. 1998. Sustainability of pinyon-juniper ecosystems: A unifying perspective of soil erosion thresholds. Journal of Range Management.
- Day, P. R. 1965. Particle fractionation and particle-size analysis. Pages 562-566 IN: C. A. Black (ed.). Methods of soil analysis Part I: Physical and mineralogical properties including statistics of measurement and sampling. American Society of Agronomy, Madison, Wisconsin.
- DeBano, L. F. 1977. Influence of Forest Practices on Water Yield, Channel Stability, Erosion, and Sedimentation in the Southwest. In Proc. Soc. Am. For. 1977 Natl. Conv. (Oct. 2-6, 1977). Soc. Am. For., Washington, D.C.
- Gottfried, G. J., T. W. Swetnam, C. D. Allen, J. L. Betancourt and A. L. Chung-MacCoubrey 1995. Pinyon-Juniper Woodlands. p. 95-132 IN: D.M. Finch and J.A. Tainter (tech. eds.). Ecology, Diversity and Sustainability of the Middle Rio Grande Basin. Gen. Tech. Report RMGTR-268. USDA Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Mitchell, J. D. 1978. The American Indian: A Fire Ecologist. American Indian Culture and Research Journal. 2(2):26-31.
- Molles, M. C., Jr., C. N. Dahm, and M. T. Crocker. 1992. Climate variability and streams and rivers in semi-arid regions. p. 197-202 IN: R.D. Robarts and M.L. Bothwell (eds.). Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management. N.H.R.I. Symposium Series 7, Environment Canada, Saskatoon.
- Morgan, R. P. C., and R. J. Rickson Editors. 1995. Slope Stabilization and Erosion Control: A Bioengineering Approach. Chapman and Hall. New York, NY.
- New Mexico Water Quality Control Commission (NMWQCC). 1994. Water Quality and Water Pollution Control in New Mexico. A Report prepared for submission to the Congress of the United States by the State of New Mexico pursuant to Section 305(b) of the Federal Water Pollution Control Act. Sept. 1994. Santa Fe, NM.
- Pase, C. P. 1981. Community structure analysis - a rapid, effective range condition estimator for semi-arid lands. Pages 425-430 in H. G. Lund, and others (tech. coord.). Arid land resources inventories: developing cost-efficient methods. USDA Forest Service General Technical Report WO-28, Washington, D.C.
- Pase, C. P., and C. E. Granfelt. 1977. The Use of Fire on Arizona Rangelands. Arizona Interagency Range Committee Publication No. 4. USDA Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. 15 p.
- Pyne, S. 1982. Fire in America: A Cultural History of Wildland and Rural Fire. Princeton University Press. Princeton, NJ.
- Shakesby, R. A. 1993. The Soil Erosion Bridge: A Device for Micro-Profiling Soil Surfaces. Earth Surface Processes and Landforms. 18:823-827.
- Vitousek, P. M., and R. W. Howarth. 1991. Nitrogen limitation on land and in the sea: how can it occur? Biogeochemistry 13:87-115.
- Watt, A. S. 1947. Pattern and process in the plant community. Journal of Ecology 35:1-22.
- Weltz, M. and M. K. Wood. 1986. Short-duration grazing in central New Mexico: effect on sediment production. Journal of Soil and Water Conservation 41:262-266.
- White, C. S. 1986. Monoterpenes: Their Effects on Ecosystem Nutrient Cycling. Journal of Chemical Ecology. 20(6): 1381-1406.
- White, C. S., and M. McDonnell. 1988. Nitrogen cycling processes and soil characteristics in an urban versus rural forest. Biogeochemistry 5:243-262.
- Wilcox, B. P. 1994. Runoff and erosion in intercanopy zones of pinyon-juniper woodlands. Journal of Range Management 47:285-295.
- Wilcox, B. P., J. Pitlick, and C. D. Allen. 1994. Frijolito Watershed: Integrated Investigations of a Rapidly Eroding Pinyon-Juniper Hillslope. Semiarid Hydrology Conference, Tucson, AZ, Nov. 1-3, 1994. LA-UR 94-3833.
- Wood, J. C., M. K. Wood, and J. M. Tromble. 1987. Important factors influencing water infiltration and sediment production on arid lands in New Mexico. Journal of Arid Environments 12:111-118.
- Wright, H. A. 1980. The Role and Use of Fire in the Semidesert Grass-Shrub Type. Gen. Tech. Rep. INT-85. USDA Intermountain Forest and Range Experiment Station, Ogden, Utah. 24 p.
- Wright, H. A., and A. W. Bailey. 1982. Fire Ecology: United States and Canada. John Wiley & Sons, Inc. New York, NY.
- Yair, A., D. Sharon, and H. Lavee. 1980. Trends in runoff and erosion processes over an arid limestone hillside, northern Negev, Israel. Hydrological Sciences Journal 25:243-255.

Watershed Health: an Evaluation Index for New Mexico

Bill Fleming

Abstract—Although watersheds are not equally healthy, there are no generally accepted criteria for evaluating and comparing them. This paper suggests several criteria which numerically evaluate watersheds in four ways: (1) riparian health, (2) aquatic macroinvertebrate biodiversity, (3) hillslope soil loss and (4) upland land use/flood peak potential. Each criterion is semi-quantitatively evaluated on a scale of 1 to 10, with 1 the healthiest and 10 the least healthy. The index is applied to two subalpine watersheds near Santa Fe, New Mexico, comparing them using the four numerical criteria. The Rio en Medio, site of the Santa Fe Ski Basin, was rated “good” (with a score of 4.1), while an adjacent undeveloped watershed, the Rio Tesuque was rated “excellent” (with a score of 2.5).

Methodology

Four methodologies for evaluating watershed health are described and then combined to form a watershed health index. An example is presented comparing two adjacent watersheds with different land uses near Santa Fe, New Mexico.

Riparian Health

Several authors, such as Barbour and Stribling (1991), have suggested criteria for evaluating the health of riparian habitats in the Western United States. Although their criteria is heavily weighted toward stream habitats for fish, the index has been adapted for a wider range of species by others (Fleming and Schrader, 1998). Ten criteria are described in table 1, beginning with stream discharge necessary to support a healthy aquatic habitat for macroinvertebrates and fish. For an optimum environment, several authors, including Barbour and Stribling (1991) consider that 0.05 m³/sec (2 cfs) are necessary to support a high-quality, coldwater fishery. If less than 0.01 cfs are flowing, the habitat is considered “poor.”

Streambed geology and embeddedness are critical for the maintenance of necessary void spaces in the substrate for macroinvertebrate habitat. If more than 50 percent of the material is comprised of grain sizes in the gravel, cobble and boulder categories, the habitat is considered “optimum.”

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Streams reaches are evaluated with a “random walk” method, in which the investigator crosses the stream in a zigzag pattern, stopping every two steps to determine the size of material in front of the instep of the wader (Sims and others 1995). At least 20 samples should be chosen in each reach and a range of grain size percentages calculated. If more than 50 percent of the substrate is sand size or smaller, the habitat is considered “poor.”

Structural vegetation diversity is important for birds and if grasses, shrubs and trees are present in the riparian zone, this criterion receives an optimum rating. Vegetation cover, expressed as a percent, is estimated by randomly choosing a transect direction to walk, noting at every other step whether or vegetation cover exists. Ninety percent vegetation cover is optimum, while less than 50 percent is considered poor. Vegetative diversity is evaluated by determining whether at least 10 different species occur in the riparian zone, which is scored as optimum (less than 3 species is considered poor). The width of the vegetation buffer is considered optimal if it exceeds 18 meters and poor if it is less than 6 m. Canopy shading is considered optimal if a mix of sun and shade, while full sun is considered poor.

The ratio of bankfull channel width to depth is optimal if less than 7 (Rosgen, 1994) and poor if more than 25 (a very wide and shallow stream). If the ratio of distance between riffles to stream width is between 5 and 7, heterogeneity for aquatic insects is optimal, while a ratio of more than 25 is considered a poor habitat (Barbour and Stribling, 1991). Upper bank stability is considered excellent if there are no vertical and unvegetated banks, while more than 50 percent of bank area in an unstable and eroding condition is rated poor.

Table 1—Riparian health indices.

Parameter Score	Excellent 0-0.1	Good 0.1-0.4	Fair 0.4-0.7	Poor 0.7-1.0
Flow (m ³ /sec)	>0.05	0.03-0.05	0.01-0.03	<0.01
Streambed geology	>50% boulders cobbles gravel	25-50%	10-25%	<10%
Embeddedness	<25%	25-50%	50-75%	>75%
Width/depth	<78-15	15-25	>25	
Bank stability	>90% stable	70-90%	50-70%	<50%
Buffer width	>18m	12-18m	6-12m	<6m
Vegetation diversity	>10 species	5-10	3-5	<3
Structural diversity	3 height classes	21	1 sparse	
Vegetation percent cover %	>90 %	70-90 %	50-70 %	<50
Canopy shading	mixed sun/shade	sparse canopy	mostly sun or shade	no shade

Biodiversity of Aquatic Insects

An important indicator of the long term health of a watershed are species of aquatic macroinvertebrates. Insects remain in streams during transitory periods of floods, drought, periods of turbidity or heavy metal inflow. The benthic insects are affected by chemical pollution and physical changes such as temperature pH, discharge and sediment resulting from upstream land use activities. Whether or not sensitive families of insects remain in a stream over the long term is a useful indicator of upstream watershed health.

Stoneflies are generally the order of insects most sensitive to human impacts such as organic sewage pollution, and if some of the more sensitive families are absent, it may be indicative of nitrogen or phosphorus in higher than natural concentrations. Usually stoneflies are a smaller percentage of the insects (10-20 percent) and may be the first to disappear with increased human impacts. Mayflies are also sensitive to watershed disturbances, but may be 20-40 percent of the total number, and may be the next to disappear in a stressed watershed. Caddisflies also include species sensitive to sedimentation, in particular, but some families are very tolerant and can live under highly disturbed conditions (for example Hydropsychidae). If an insect collection is dominated by midges or worms, the watershed and stream may be very degraded. The different families, and percentages of each family, are indicators of the health of the watershed.

The tolerance to watershed disturbance of the families of aquatic insects occurring in New Mexico is shown in table 2 (based on Winget and Mangum, 1979 and interpreted by Jacobi, personal communication, 1996). Higher numbers mean the insect is more tolerant to watershed disturbance, and those with an index of 10 may survive in stream systems with high concentrations of sediment, nutrients and metals. Low indices indicate that the family is sensitive to watershed disturbances (such as the Pteronarcyidae family of giant stoneflies which dominates the upper Pecos watershed).

To determine the biotic tolerance index for a watershed above a sampling site, at least 100 insects are collected and the numbers of each family determined. Numbers of each family are multiplied by the tolerance index, and these values added. The total number is then divided by the number of insects collected to determine a biotic index for the watershed or stream reach. If the index is less than 3.5, the watershed condition may have little upstream disturbance, whereas values exceeding 7.5 may be highly impacted.

Hillslope Soil Loss

The Universal Soil Loss Equation has been used to predict erosion rates in the Midwest for over 40 years, but only recently has been adapted for Western forest and range lands (Brooks and others 1997). In the West, the form of the equation is usually the "modified" variety because the vegetation factor is better suited to forest and range lands than the "agricultural practice" factor validated for hundreds of erosion plots in the Midwest. The "modified universal soil loss equation" (MUSLE) is used here as an indicator of

Table 2—Tolerance index for New Mexico macroinvertebrates.

Order	Family	Tolerance index (10= most tolerant)
Ephemeroptera (Mayflies)	Tricorythidae	10.0
	Baetidae	6.7
	Siphonuridae	6.7
	Caenidae	6.7
	Ephemerellidae	4.4
	Heptageniidae	4.4
	Leptophlebiidae	3.3
Plecoptera (Stoneflies)	Perlodidae	4.4
	Taeniopterygidae	4.4
	Nemouridae	3.3
	Capniidae	3.0
	Pteronarcyidae	2.2
	Chloroperlidae	2.2
	Perlidae	2.2
	Leuctridae	1.7
Trichoptera (Caddisflies)	Hydropsychidae	10.0
	Limnephilidae	10.0
	Psychomyidae	10.0
	Leptoceridae	5.0
	Brachycentridae	2.2
	Lepidostomatidae	1.7
	Rhyacophilidae	1.7
Coleoptera (Beetles)	Elmidae	10.0
	Hydrophilidae	6.7
	Dytiscidae	6.7
	Halipilidae	5.0
Odonata (Dragonflies and Damselflies)	most families	10.0
Diptera (Aquatic Flies)	most families	10.0
Non-insects (snail, leeches, aquatic worms etc.)	most families	10.0

upland watershed health because it integrates four factors critical in evaluating hillslopes: (1) precipitation intensity, (2) slope steepness and length, (3) soil stability, and (4) vegetation cover.

The power of high-intensity, short-duration rainstorms to erode soil in New Mexico watersheds has been evaluated by the Soil Conservation Service (now the National Resource Conservation Service, USDA, 1977), and dimensionless values generally increase with elevation. In the Rio Grande Valley near Albuquerque, rainfall intensity corresponds to a contour with a value of "20", whereas the crest of Sandia Peak has a value of "60" with much more powerful summer rainfall impact on soil.

With steeper and longer slopes, runoff will attain higher velocities and erode more soil, if other factors remain the same. Watershed management texts interpret "slope factors" to be used in the soil loss equation (Brooks and others 1997). Slope steepness is quickly measured in the field with a clinometer and slope length determined with topographic maps.

Depending on the grain size composition, percent of organic matter and infiltration capacity of soil, erosion potential changes (Brooks and others 1997). Soil surveys evaluate the "K factor", or erodibility factor, for soils, or publish grain size compositions which allow K factors to be calculated.

While the previous three factors in the soil loss equation usually remain the same with watershed disturbance, the vegetation cover may change significantly when development occurs. Activities such as logging, grazing, ski trail construction, roads, and housing development reduce the vegetation cover, sometimes eliminating the most important factor in protecting soil from intense rainfall. Watershed management texts list vegetation cover factors with varying grass cover percentages and types of overstory protection (Brooks and others 1997). Field surveys of cover percent are made by randomly choosing several hillside transects and pacing 10 steps per transect, noting whether or not the front of the pace has vegetation cover or bare soil.

The four factors are then multiplied together, resulting in soil loss in tons/acre/year. While forest and range landscapes in the Western United States have not been validated with same rigor as agricultural lands in the Midwest, values of relative erosion rates are useful in rating watershed health. The NRCS estimates that “tolerable” soil losses are those exceeding 5 tons/acre/year, while Pimentel (1995) cites evidence that 0.5 tons/acre/year is an average worldwide value for the rate of soil formation (lower in arid regions and higher in humid landscapes).

A simplified health index for soil loss relates erosion rates to a what could be considered a sustainable rate of 1 ton/acre/year, which receives an “excellent” rating of one. As rates increase, the rating increases, with a soil loss of 10 tons/acre/year having a rating of 10 (poor watershed condition). It is important to realize that many landscapes in New Mexico have erosion rates exceeding 10 tons/acre/year, resulting in a “poor” rating for these areas.

Upland Land Use and Flood Peak Impacts

Land use in upper watersheds clearly has impacts on watershed health and downstream flood peaks. For watersheds of less than a square mile, the “rational equation” is often used by planners to predict downstream flood peaks, based on watershed area, hourly rainfall intensity and a land use factor. For larger and more diverse watersheds, a method developed by the former US Soil Conservation Service (now the NRCS), using runoff curve numbers, is a generally accepted approach (Brooks and others 1997). The SCS approach is similar to the rational method, but uses a “runoff curve number” to evaluate land use and the watershed’s hydrologic response in the form of flood peaks.

Since the objective here is not to predict changes in flood peaks with land use alterations, but only to indicate the critical factor involved in flood peak modifications, the curve number will be used as an indicator for upland land use as it relates to flood peak generation. As published by the SCS in 1972, runoff curve numbers range from 6 to 94, depending on the type of land use and how it impacts the infiltration of surface runoff into the vegetation/soil cover. Lower numbers indicate high infiltration rates and high numbers low infiltration rates and consequent high flood peaks (Brooks and others 1997). Table 3 shows one version of curve numbers, and these are modified simply by division by 10 so the index will correspond to the other three parameters in this analysis.

Table 3—Runoff curve numbers and watershed land use (Marsh, 1998 and Brooks and others 1997).

Land use	Curve number
Commercial (roads, shopping centers)	7.0-9.5
Residential (single family)	3.5-5.0
(multifamily)	6.0-7.5
Industrial (light)	5.0-8.0
(heavy)	6.0-9.0
Parks	1.0-2.5
Playgrounds	2.0-7.5
Cultivated farmland (flat)	1.0-4.0
(rolling: 5-10 percent slope)	2.5-5.0
(hilly: 10-30 percent)	3.0-6.0
Rangeland (poor condition)	7.0-9.0
(fair condition)	5.0-8.5
(good condition)	4.0-8.0
Forest (poor condition)	4.5-8.5
(fair condition)	3.5-8.0
(good condition)	2.5-7.5

Application to Watersheds Near Santa Fe

The methodology is applied to two adjacent watersheds in the Santa Fe National Forest, 15 miles northeast of Santa Fe, New Mexico in the Sangre de Cristo Mountains. Each watershed is slightly over one square mile in area, ranging in elevation from 9,800 feet to 11,100 feet. The Rio en Medio watershed is the site of the Santa Fe Ski Basin, in which approximately 35 percent of watershed area has been developed with parking lots, lodges, septic tank fields, ski runs and lifts. The Tesuque watershed is in a relatively undeveloped condition, with one road used only for hiking, ski touring and the maintenance of telecommunications antennae on Tesuque Peak. Table 4 summarizes the results.

Riparian health: Two riparian surveys were done in each watershed, one at the base and a second approximately 0.3 miles upstream. Results of the two surveys were averaged for each watershed. The Rio en Medio had an average rating of 2.6 and Tesuque Creek 0.7. Major differences were less riparian vegetation and more sediment and embeddedness in the Rio en Medio.

Biodiversity of aquatic insects: A total of 486 insects were collected from the Rio en Medio and 518 from the

Table 4—Watershed health indices for Santa Fe watersheds.

Watershed health index	Rio en Medio	Rio Tesuque
Riparian health	2.6	0.7
Macroinvertebrate biodiversity	4.3	3.1
Hillslope erosion rates	2.2	0.7
Land use/flooding potential	7.3	5.5
Total (divided by 4 indices)	4.1	2.5

Rio Tesuque by the Santa Fe Preparatory School during 1993-94. Rio en Medio had an index of 4.3 and Tesuque Creek 3.1, mainly resulting from a greater percentage of stoneflies in the Tesuque (29 percent compared with 19 percent in the Rio en Medio).

Hillslope soil loss: Surveys on three slopes in both watersheds indicate an average erosion rate in the Rio en Medio of 2.2 tons/acre/year, compared with 0.7 tons/acre/year in the Tesuque. The difference results from hillslopes in the Rio en Medio which have lower vegetation cover percentages than the Tesuque.

Upper land use and flood peak impacts: Evaluations of land use in the Rio en Medio resulted in a runoff curve number of 7.3 because of the extensive ski area development. The relatively undeveloped Tesuque watershed had a lower curve number of 5.5. The flooding potential of both watersheds is relatively high for forested areas because of thin soil covers which don't store large amounts of soil moisture and ground water for later baseflow.

References

- Barbour, M.T. and J.B. Stribling. 1991. Use of habitat assessment in evaluating the biological integrity of stream communities. *Biol. Criteria: Research and Regulation*: 25-38.
- Brooks, K., Ffolliet, P., Thames, J. and Gregerson, H. 1997. *Hydrology and the management of watersheds*, 2nd ed., Iowa State Univ. Press, 547 p.
- Fleming, W.M. and R.E. Schrader. 1998. *New Mexico Watershed Watch Handbook*. NM Game and Fish Dept. Special Report, 56 p.
- Pimentel, D. 1995. *Soil erosion worldwide*. Cornell Press, 468 p.
- Rosgen, D. 1994. River restoration utilizing natural stability concepts. *Land and Water*, July/Aug: 36-40.
- Sims, B., J. Piatt, L. Johnson, C. Purchase and J. Phillips. 1995. Channel bed particle size distribution procedure used to evaluate watershed cumulative effects for range permit re-issuance on the Santa Fe National Forest. *USDA Forest Service Technical Rpt.*, Santa Fe National Forest, Santa Fe NM, 12 p.
- USDA, 1974. *Rainfall intensities for New Mexico*. Soil Conservation Service Ag. Bull. 568.

A Constructed Wet Meadow Model for Forested Lands in the Southwest

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Abstract—Improving primary roads in the Zuni Mountains of New Mexico must take into consideration the wet meadows and upland areas. This study looks at spring flow rates, erosion, channels and changes in plant cover and composition. The goal is to help planners design environmentally sensitive roadways for wet meadow areas.

Wet meadows occur naturally in the high elevations of the Zuni Mountains of New Mexico. These areas typically have higher diversities of plant and animal species than adjoining upland areas due to the availability of permanent or semi-permanent water sources. The low-lying nature of these areas has typically made them more suited for transportation routes and easier crossings than the immediate surroundings. Road and railway beds built in these areas often constrict and cut off the natural flow of water through these areas. Constriction and blockage of natural drainage ways can lead to incised channels and lowered water table levels. The vegetation in these areas typically changes from mesic to xeric in response to the decreased water availability.

The roads staff on Cibola National Forest in New Mexico are working to improve primary roads in the forest that have deteriorated and do not provide safe, year round access. In addition, they are obliterating abandoned roads and railroad grades originally built to remove timber from the forest. The design and construction practices used for new roads considers them as part of the ecosystem. In areas where the roads intersect drainages, structures are installed to permit water to pass beneath the road surface unobstructed. Structures used include multiple raised culverts spread across meadow crossings and French drains. Both types of structures limit the concentration of surface flows. Eroded channels and dewatered meadows as a result of improper road designs and construction practices can be observed along unimproved forest roads in the Zuni Mountains. The damage created by these inappropriate designs and practices can often be corrected and the areas rehabilitated.

Agua Fria meadow in the Zuni Mountains, 32-km southwest of Grants, New Mexico is a forest meadow that showed evidence of having been a wet meadow. Observations by

forest personnel designing improvements for Forest Road 49 through the meadow, suggested that the area could have been dewatered because of the location of old transportation routes and drainage structures. A plan was developed and implemented to rewet the meadow.

Before the road and meadow projects, Agua Fria was a broad meadow with a relatively straight, 2-3 m deep, entrenched channel running down one side, that quickly funneled runoff through the area from the upper watershed. Several abandoned railroad beds and Forest Road 49 crossed the meadow, perpendicular to the direction of water flow. The vegetation cover across the meadow was a mixture of xeric grasses, shrubs and forbs with a few large Ponderosa Pine and Juniper trees scattered throughout the area.

During the construction phase, the entrenched channel was back-filled in sections to prevent water from flowing in it. Beginning near the top of the meadow, a new highly sinuous channel, .6 m deep, was constructed down the center of the meadow. The channel was built to create a step-pool sequence type flow pattern. Straight channel sections form the steps and curved bank sections, reinforced with tree stumps serve as the pools. The beginning and end of each channel section is delimited by a rock weir structure that concentrates water flowing in the channel. Concentration of the flow in the channel keeps soils and other materials suspended in the runoff from settling to the bottom. The roadway across the meadow was built on top of an earthen berm elevated almost 2 meters at the high point. Sixteen culverts were installed through the berm, spaced across the active runoff section of the meadow to permit water to flow underneath the roadway with minimal obstruction. At the down stream end of the meadow, the new channel was merged with the old channel. Meadow areas disturbed during construction were tilled and planted with a mixture of native grass seed to encourage the quick establishment of vegetative cover to prevent soil erosion. The construction phase of the project was terminated in the fall of 1996.

The channel and roadway projects have been monitored since completion by regular visits to the site. Runoff has only been observed flowing in the channel during the spring while snow was melting on the upper watershed. Runoff can also be generated by large rainfall events. However, observations of the channel during the non-winter months have not demonstrated that rainfall has generated adequate runoff to promote continuous flow in the channel. Spring runoff in 1996 and 1997 rarely produced flows that exceeded the bank full stage of the new channel. Erosion and deposition in the channel was negligible in these years. Seed planted in the areas disturbed during construction germinated, but did not grow well.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Spring runoff in 1998 began in March and flowed continuously until the end of May. Runoff exceeded the bank full stage along most reaches of the channel until early April after which regular flow measurements were continued. A channel flow rate at slightly below bank full capacity was measured and determined to be 34 cfs. We will attempt to estimate what the maximum flow rates could have been using high water marks noted upstream from the project area. The high runoff rates observed during the spring of 1998 correspond with the 23 percent higher than the average annual precipitation observed for this area. Runoff eroded and breached the channel in a number of locations, which was expected. However, in one channel section towards the lower end of the project, water that breached the channel was inadvertently diverted away from the new channel into the former channel. It was estimated that more than half of the above bank full flow was diverted at this point towards the old channel. The runoff flowed along an old road and then along the course of the old channel. Most of the old channel had been back filled from upstream to the lower end of the project, so the water actually flowed on top of the backfill. These overland flows created several long and deep head cuts and gullies from the lower junction of the old and new channels moving up the meadow.

Vegetation in the seeded and undisturbed areas grew tall and dense during the spring and summer of 1998. A vegetation survey will be conducted in October 1998 to compare plant cover and composition with pre-project conditions measured in the fall of 1994. The roadway was not affected in any way by the runoff across the meadow.

Forty-five piezometers were installed across Agua Fria meadow during September and October 1998 to monitor the depth and distribution of the water table. The drilling records will be used to determine the makeup of the subsurface soil layers. Forty 3-m deep wells were installed along 5 rows, uniformly spaced down the length of the meadow. The remaining five wells were installed one per row, to a depth of 10 m. During installation of the 10 m wells, freestanding water was encountered at 9 m below the soil surface. Bedrock was encountered in one well at 10 m. The soil profile in most wells consisted of thick clay layers divided by thin layers of sand and gravel.

The hydrologic conditions required to support a wet meadow currently do not exist in the Agua Fria meadow, based on our observations to date. We anticipate that the recently elevated channel will direct sufficient spring runoff onto the meadow surface and into the subsurface layers that a permanent to semi-permanent water supply is established that will support wet meadow plant species. In the meantime, our investigations are helping us understand how Agua Fria meadow and Forest Road 49 function and change in response to our interventions.

The results of our investigations will provide information to resource managers and roadway planners that can help them design environmentally sensitive roadways for wet meadow areas. In addition, our results will document the effectiveness of stream channel redirection as a method to rewet a dewatered forest meadow.

Effect of Spatial and Temporal Variability on Water Relations and Growth in Pinyon Pine: III. Whole Tree Response

Teresa L. Newberry

Abstract—This paper is the final report in a larger study of water relations in pinyon pine ecosystems. This last study looks at whole-tree response to climatic variability; water use efficiency was studied using ^{13}C measurements of tree-rings.

The purpose of this study is to explore the physiological response of pinyon pine to spatial and temporal variability on a whole tree level using information on physiology and growth recorded in tree-rings. The rationale of this approach is that water relations of pinyon pine and any long-lived species can only be truly understood in the context of the spatiotemporal heterogeneity inherent to natural environments. In addition to providing a more complete characterization, exploring a wide range of spatial and temporal scales can lead to deeper ecological insights (Betancourt 1993, Ehleringer & Field 1993, Gosz, J.R. 1993, Gosz and Sharpe 1989, O'Neill 1986). In semiarid regions, annual precipitation provides a dominant limitation of the ecosystem biomass, but is insufficient for predicting community structure and composition. Rather, temporal variability in precipitation has been hypothesized to more directly constrain community structure (Noy-Meir 1993, Crawford & Gosz 1982, Neilson and others 1992, Sala and others 1992). In addition to temporal variability, the high degree of spatial variability inherent in natural environments also plays an important role in community and ecosystem dynamics (Bazzaz 1993).

This study is the final part of a larger study that explores the water relations in pinyon pine on a variety of spatial and temporal scales. The first stage of the study examined physiological responses at a stomatal level measuring instantaneous and seasonal responses to changes in soil and atmospheric moisture. The second stage of this study measured physiological response at a needle level integrating stomatal responses at annual and interannual time scales. This study measures whole-tree response to climatic variability using tree-rings and represents an integrated response of both stomata and different-aged needle cohorts over a period of five years. These layers of complexity in water relations of pinyon pine have been examined in order to answer such questions as: Which climatic variables are

most important in affecting stomatal behavior and water use efficiency and at what scale are they important: diurnal, seasonal or annual? What is the diversity in physiological response between individuals? Is there a physiological difference between ecotonal, xeric sites and mesic sites?

Since maximizing carbon gain and minimizing water loss can be crucial in arid ecosystems where water is limiting, the ability to adjust water use efficiency in response to changing availability of water is an ecologically important characteristic. In this study, water use efficiency is studied using ^{13}C measurements of tree-rings. The development of isotopic models relating ^{13}C to water use efficiency (Farquhar and others 1982) has shown great promise in providing physiologists with a powerful tool to investigate physiological response at scales of growing seasons (Farquhar and others 1988, Leavitt & Long, 1989, Leavitt 1994). Net instantaneous water use efficiency (WUE), the ratio of carbon assimilation to evapotranspiration, has been found to correspond to high ^{13}C —high ^{13}C values corresponding to high water use efficiency and vice versa (Farquhar and others 1988). For long-lived species such as trees, combining this technique with tree-ring analysis provides a long-term record of physiological response to changing climatic regimes.

Specifically, this part of the study will address the following questions:

1. Does water use efficiency change from year to year in response to climatic patterns?
2. Does the whole tree response differ from the response of different-aged needle cohorts?
3. Is winter or summer precipitation more important in determining water use efficiency and growth in pinyon pine?
4. Is the physiological response different at an ecotonal/xeric site than at a more mesic site?
5. Is there a relationship between the plasticity of water use efficiency and growth?

Methods

Site Description

The field sites are located in the Los Pinos Mountains on the Sevilleta LTER in central New Mexico. There are two field sites within about 3 to 4 kms of each other—one at 1700 m and the other at 2000 m elevation. Although the two sites are in close proximity with only a small elevation change, the site characteristics differ quite markedly. Goat

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Draw, is an open woodland located at the pinyon-juniper woodland/juniper-grassland ecotone. The higher site, Cerro Montoso, is a densely vegetated pinyon-juniper stand. The lowest elevation site is representative of pinyon-juniper to juniper-grassland ecotone. The density of pinyon pine is much lower relative to the density of juniper. The higher elevation site is representative of pinyon in the middle of its range. Both sites are located on slopes of 10 to 20 degrees with N-NW facing aspects. The soils of both sites are derived from a granitic substrate and are coarse-grained in texture. The physiological characteristics of both sites have been studied extensively in previous studies. The Goat Draw site is also an LTER site where population, growth and physiological characteristics have been studied.

Sample Collection

Cores were collected from four individual trees from each site. The trees selected were those from which extensive physiological measurements had been made in the previous portion of this project. Two cores were collected from each tree: one in the north cardinal direction and one in the south cardinal direction. The cores were surfaced and dendrochronologically dated. The rings from individual years 1990 to 1986-1984 were separated under a binocular microscope using a razor blade combining the material from the north and south cores and analyzed for ^{13}C . The samples chosen for wood analysis were the same years on which leaf ^{13}C analysis had been conducted. Leaf ^{13}C analysis was dependent on the retention time of the needles.

Isotope Analysis

Isotope analysis was conducted on the cellulose isolated in a procedure after Green (1963) as modified by Leavitt and Danzer (1994) for small samples. The samples were combusted to carbon dioxide in an oxygenated atmosphere at 800°C in a recirculating microcombustion line. The carbon dioxide was analyzed mass-spectrometrically and ^{13}C was computed relative to the PDB standard (Craig 1957). All analysis was conducted at University of Arizona Laboratory of Tree-ring Research.

Climate Data

Monthly PDSI and precipitation values were obtained from Socorro Weather Station. Annual Palmer Drought Severity Index (PDSI) and precipitation was represented by taking the mean value from October of the previous year until October of the current year. Winter PDSI and precipitation was presumed to be represented by the mean values from the months of November of the previous year until March of the current year. Summer PDSI and precipitation was estimated by taking the mean of the monthly values from the period July to October.

Results

Variation in ^{13}C Over Time

The results of ^{13}C analysis of wood shows the year to year variation in water use efficiency in pinyon pine (fig. 1). These

results show that although patterns for individuals through time are very similar, the absolute values vary between individuals. This would suggest that while individual trees have different water use efficiencies, their response to year to year climate variability is similar. These results are very similar to those of Leavitt (1994) which showed that the absolute values varied among individuals of same species at a site while the patterns through time were similar in both coniferous and deciduous trees. The most marked feature of these patterns is the dramatic increase in ^{13}C for all trees at both sites in 1989. For the most part the weather patterns during the years measured were close to normal years of precipitation, 1989, however, was an extremely dry year. There does not appear to be much difference in the range and patterns of ^{13}C between sites. The mean value and standard deviation of ^{13}C values at Goat Draw is $-20.66 \pm .66$ and at Cerro Montoso it is $-20.71 \pm .75$.

The carbon isotope values of annual rings in pinyon pine represent the integrated measure of water use efficiency of

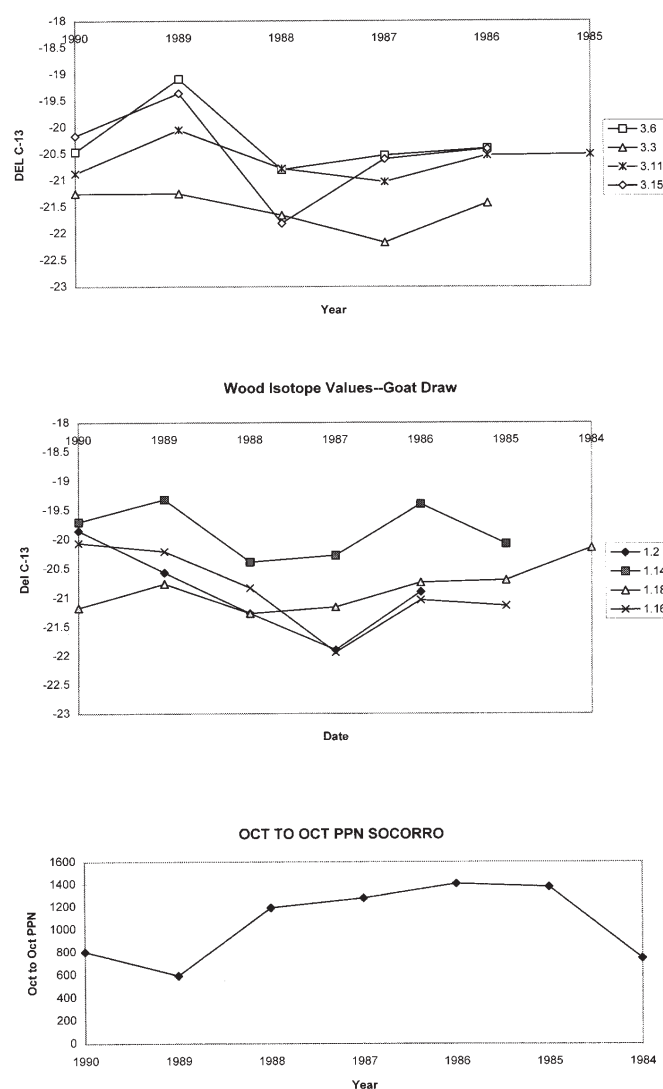


Figure 1—Results of isotope analysis on wood at Goat Draw and Cerro Montoso.

all leaf cohorts over whole tree over the course of a year with some lag factors due to carbon translocation and storage. Typically, needle retention in pinyon pines at these sites is between five to seven years. A comparison of same year needle and annual ^{13}C values show that while the wood values tend to be isotopically lighter the patterns of changes from year to year are very similar (fig. 2, 3). The fact that the patterns of ^{13}C are similar to ^{13}C in needles suggests that

the overall water use efficiency of the tree is most likely under physiological control (i.e., the instantaneous response of stomata to changes in water status) rather than anatomical control (i.e., wax layers, number of stomata, sunkness of stomata, photosynthetic efficiency, etc.). It also suggests that decreased water use efficiency due to aging of needles is not an important factor determining the overall water use efficiency of the whole tree.

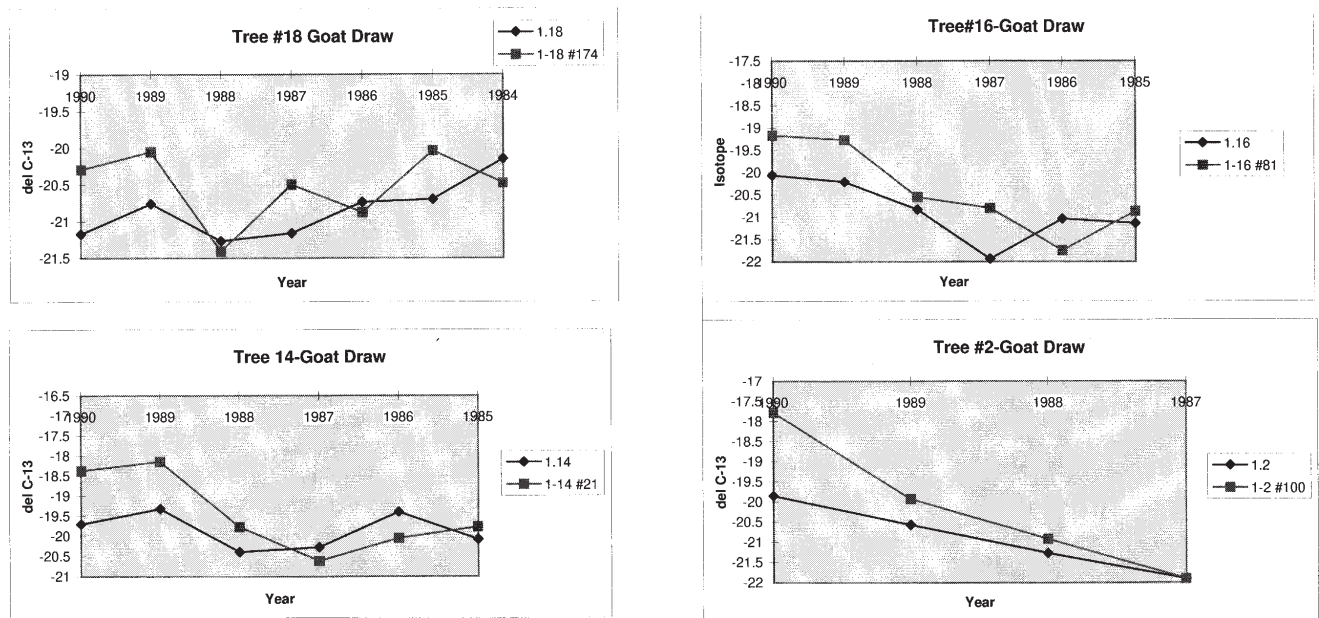


Figure 2—A comparison of leaf and wood isotope values for Goat Draw.

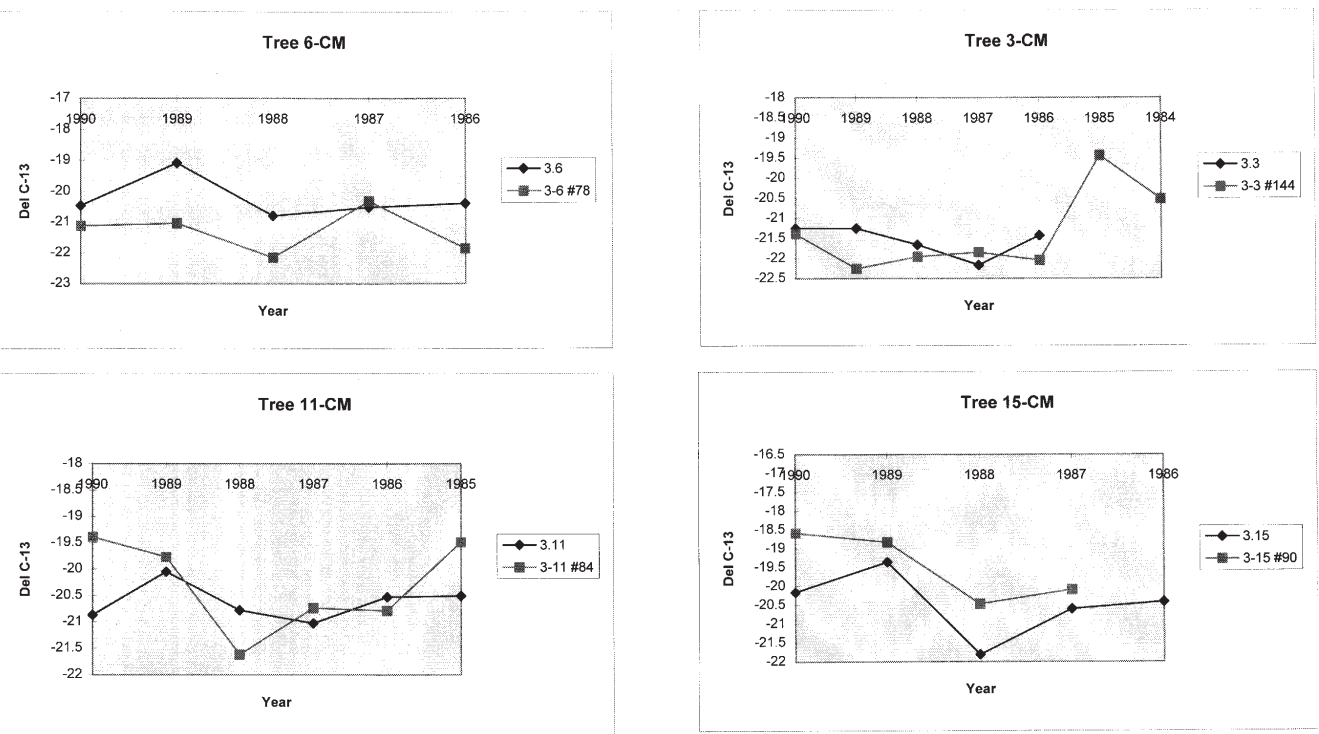


Figure 3—A comparison of leaf and wood isotope values for Cerro Montoso.

Table 1—Results of regression analyses of climate vs. C¹³ values for Goat Draw—r² values.

Tree #	October to October		July to October		November to March	
	PDSI	PPN	PDSI	PPN	PDSI	PPN
Tree#2	.87	.43	.76	.05	.92	.88
Tree#14	.39	.23	.31	.03	.38	.45
Tree#16	.93	.61	.83	.04	.92	.51
Tree#18	.09	.08	.04	.01	.07	.00
Site average	.57	.34	.49	.03	.57	.46

Relationship of Climate with ¹³C

This next section explores the relationship between ¹³C and climate. Since the absolute values of ¹³C varied from tree to tree separate regressions were done for each individual tree and ¹³C for the site was obtained by taking the average of the correlation coefficients for individual trees. Based on the typical rainfall cycles in New Mexico, three periods were considered with respect to ¹³C values: annual (October to October), winter (November to March) and summer (July to October).

Goat Draw—Results of regression analyses show that October to October PDSI has a strong influence on the isotopic composition of the wood in pinyon pine ($r^2 = .57$) while October to October precipitation has only a moderate influence ($r^2 = .34$) (see table 1 and fig. 4). There is a large spread of responsiveness to PDSI from individual to

individual. In the summer the difference in response to PDSI vs. precipitation is most pronounced ($r^2 = .49$ v. $r^2 = .03$). This reflects the importance of evaporative demand as well as water availability. These results are consistent with studies on stomatal response to vapor pressure deficit which showed that stomatal conductance is sensitive to changes in vapor pressure deficit and relative humidity as well as leaf water potential (Newberry, in prep.). In the winter PDSI and precipitation have roughly equal influence on carbon isotope values ($r^2 = .57$ v. $r^2 = .46$) and, therefore, one may conclude that evaporative demand does not play an important role in winter due to cool temperatures. Both winter PDSI and summer PDSI are equally important in determining ¹³C values in pinyon pine ($r^2 = .57$ v. $r^2 = .49$) while winter precipitation is much more important than summer precipitation ($r^2 = .46$ v. $r^2 = .03$). One interpretation of this is that winter precipitation plays a greater role than summer

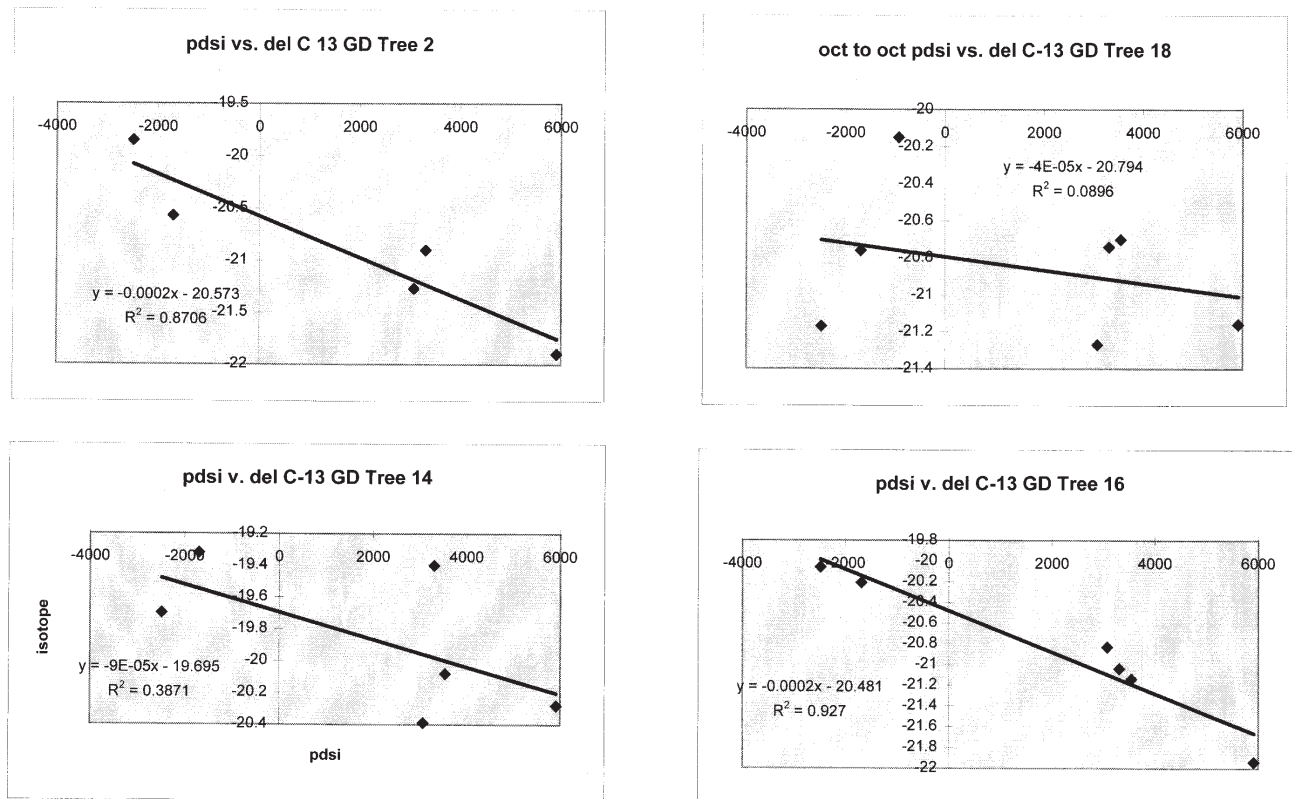


Figure 4—October to October PDSI and carbon isotope values at Goat Draw.

Table 2—Results of regression analyses of climate vs. C¹³ values for Cerro Montoso—
r² values.

Tree #	October to October		July to October		November to March	
	PDSI	PPN	PDSI	PPN	PDSI	PPN
Tree#3	.30	.38	.33	0	.24	.98
Tree#6	.78	.54	.62	.07	.78	.14
Tree#11	.19	.18	.13	.05	.16	.06
Tree#15	.34	.41	.36	.37	.32	.19
Site average	.40	.38	.36	.12	.38	.34

rainfall in determining water use efficiency in pinyon pine for the subsequent growing season due to recharge of soil water by snowfall while overall weather conditions (reflected in PDSI) of both seasons play the strongest role.

Cerro Montoso—Overall the response of PDSI and precipitation was lower at Cerro Montoso than at Goat Draw (table 2 and fig. 5). For example at Goat Draw r² was .57 for October to October PDSI while at Cerro Montoso it was .40. This is consistent with previous results which showed that the stomata of the trees at Goat Draw were more sensitive to changes in environmental conditions than at Cerro Montoso (Newberry, in prep.). Like Goat Draw, summer PDSI had a greater effect on carbon isotope values and thus water use efficiency than summer precipitation (r² = .36 v. r² = .12). Like Goat Draw, ¹³C values were equally dependent on

winter PDSI and winter precipitation. Also winter and summer PDSI were equally important in determining the annual water use efficiency of pinyon pine.

Growth and Climate

At Goat Draw growth is most strongly dependent on October to October PDSI (r² = .70) (table 3). This relationship is curvilinear. October to October precipitation also plays an important role in determining the annual growth rate in pinyon pine (r² = .55). Summer and winter PDSI and precipitation appear to have equal importance in determining growth rates. There is some variability in growth response of individuals, but not as great as the range of water use efficiency response (r² = .57 to .85 for Oct to Oct.

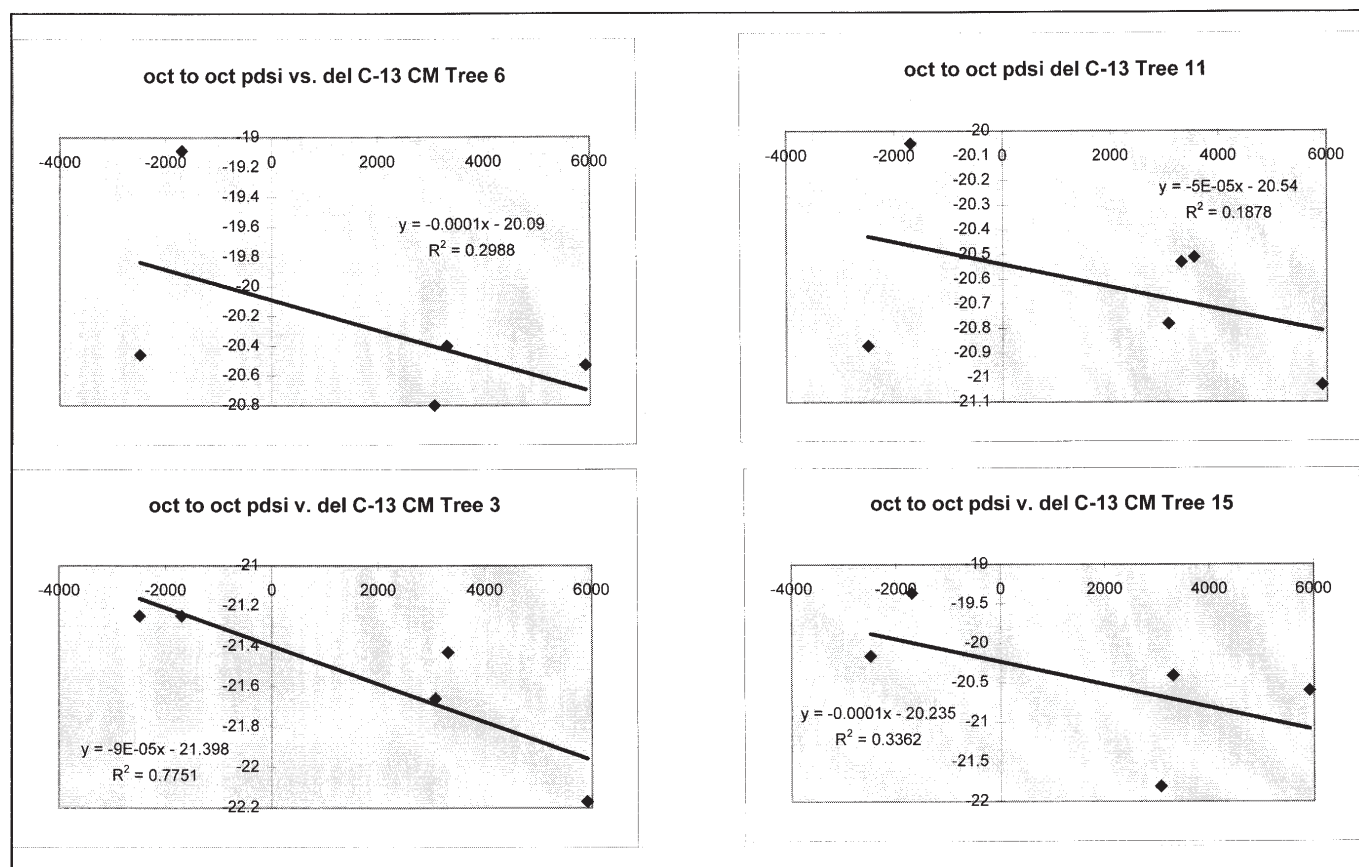


Figure 5—October to October PDSI and carbon isotope values at Cerro Montoso.

Table 3—Results of regression analyses of climate vs. growth for goat draw and Cerro Montoso- r^2 values.

Tree #	October to October		July to October		November to March	
	PDSI	PPN	PDSI	PPN	PDSI	PPN
Goat Draw	.70*	.55	.54	.31	.62*	.30
Cerro Montoso	.54*	.49	.62*	.22	.48*	.33

*curvilinear relationship

PDSI & growth). Some trees had a curvilinear growth response while in others the relationship was linear.

At Cerro Montoso growth is most strongly dependent on July to October PDSI ($r^2 = .62$) although this is only just slightly greater than the correlations with October to October PDSI ($r^2 = .54$) and November to March PDSI ($r^2 = .48$). These relationships are curvilinear. October to October precipitation has an r^2 of .49. Similar to Goat Draw some trees have a linear growth response while others have a curvilinear growth response. There is also a range of growth responses ranging from $r^2 = .49$ to .87 for July to October PDSI & growth.

Growth and Water Use Efficiency

A question of great ecological significance is do the trees with the ability to increase their water use efficiency during periods of drought have higher growth rates. Unfortunately, it is impossible to answer this question directly because in years of drought, growth rate is reduced. The relationship between growth and physiological response to climate can be examined indirectly however using several different approaches. The following questions could be asked: Does the ability of individual trees to respond to drought by maximizing water use efficiency increase the total growth over the time period studied? And, does a strong correlation of ^{13}C with climate mean a higher year to year variability in growth? Regarding the correlation coefficients of ^{13}C and annual PDSI, total growth over the period studied, and the standard deviation of annual growth over the period studied, there does not appear to be any relationship between any of these variables. This does not mean that water use efficiency does not maximize growth in pinyon pine, but instead that other factors influencing growth such as photosynthetic rates, duration of photosynthesis and total leaf area are very important in determining growth rates in pinyon pine.

Conclusions

Water use efficiency in pinyon is variable from year to year in response to PDSI. Precipitation plays a secondary role relative to PDSI in determining water use efficiency especially in the summer months when evaporative demand is high. These results are consistent with previous studies which have shown the stomata to be sensitive to both soil moisture and vapor pressure deficits (Newberry, in prep.). Both winter and summer PDSI are equally important in determining water use efficiencies in pinyon pine. Winter

PDSI is most likely very important because of the winter precipitation recharges soil water by snowfall prior to the next year's growing season.

At Goat Draw growth is most highly dependent on October to October PDSI while at Cerro Montoso, Cerro Montoso is most highly dependent on July to October PDSI although this is just slightly greater than the dependence on October to October PDSI. A comparison of the summer and winter PDSI and precipitation shows that both seasons are important in determining growth rates for both Goat Draw and Cerro Montoso.

The patterns of wood isotope values through time are very similar to the leaf patterns although the wood tends to be isotopically lighter than the leaf material. This result suggests that the overall water use efficiency of the whole tree is a function of physiological factors such as the instantaneous response of stomata to changes in water status rather than anatomical factors such as wax layers, number of stomata, sunkenness of stomata, photosynthetic efficiency, etc. It also suggests that decreased water use efficiency due to aging of needles is not an important factor in determining the overall water use efficiency of the whole tree and the ^{13}C composition of the tree.

Although patterns of ^{13}C through time are very similar among individuals at both sites, there is a high range in absolute ^{13}C values and thus one would conclude that there are differences in water use efficiencies between individuals. The results of the regression analyses of ^{13}C with climatic factors show that there is also a range in the responsiveness of water use efficiency to year to year changes in weather conditions—although as mentioned above the trees almost always move directionally in the same way. My attempt to show that trees that were able to increase water use efficiency would have higher growth rates was unsuccessful. This is most likely because other factors contributing to growth such as total leaf area, time spent photosynthesizing and photosynthetic rates also play an important role in determining growth rates. In fact, results of a previous study show that pinyon is a drought avoider and will completely shut its stomata in response to drought as opposed to keeping stomata open while increasing water use efficiency (Newberry, in prep.).

Although, the mean and standard deviation of ^{13}C values the two sites were identical, there were differences in the correlations of ^{13}C to year to year changes in climate. Goat Draw trees more strongly tracked changes in annual precipitation and PDSI than Cerro Montoso trees and their growth was more dependent on climate. This result is consistent with previous results which showed that stomata of the trees are much more sensitive to changes in

environmental conditions than at Cerro Montoso (Newberry, in prep.) Since the standard deviation at both sites is nearly identical while the correlation with climate is different, one may conclude that Cerro Montoso is responding other sources of variation. These sources of variations could be biotic in origin such as shading, herbivory and competition for water since the higher elevation site is more densely vegetated.

References

- Betancourt, J.L., Pierson, E.A., Rylander K.A., Fairchild-Parks, J.A. and J.S. Dean (1993) Influence of history and climate on New Mexico Pinyon-Juniper Woodlands. *Proceedings—Managing Pinyon-Juniper Ecosystems for Sustainability and Social Needs*.
- Bazzaz (1993) Population and Community Perspectives. In *Scaling Physiological Process: Leaf to Globe*. (Ehleringer, J.R. and Field, C.B. eds.) pp. 223-251. Academic Press, San Diego.
- Craig, H. (1957) Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of CO₂. *Geochim. Cosmochim. Acta* 12:133-149.
- Crawford, S.C. and J.R. Gosz (1982) Desert ecosystems: their resources in space and time. *Environmental Conservation*. 9:81-195.
- Ehleringer, J.R. and C.B. Fields (1993) In *Scaling Physiological Process: Leaf to Globe*. Academic Press, San Diego.
- Farquhar, G.D., Hubick, K.T., Condon, A.G., and R.A. Richards. (1988) Carbon isotope fractionation and plant water-use efficiency. In *Stable isotopes in ecological research*. (Rundel, P.W., Ehleringer, J.R. and K.A. Nagy, eds.) pp. 21-40. Springer-Verlag, New York.
- Farquhar, G.D., O'Leary, M.H., and J.A. Berry (1982) On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Austr. J. Plant Physiol.* 9:121-137.
- Gosz, J.R. (1993) Ecotone Hierarchies. *Ecol. Appl.* 3(3):369-376.
- Gosz, J.R. and P.J.H. Sharpe (1989) Broad-scale concepts for interactions of climate, topography and biota at biome transitions. *Landscape Ecology* 3:229-243.
- Green, J.W. (1963) Wood cellulose. In *Methods of Carbohydrate Chemistry*. (Whistler, R.L., ed.) pp. 9-21. Academic Press, New York.
- Leavitt, S.W. (1993) Seasonal ¹³C/¹²C changes in tree rings: Species and site coherence, and a possible drought influence. *Can. J. For. Res.* 23:210-218.
- Leavitt, S.W. and Danzer, S. 1993. Method for Batch Processing Small Wood Samples to Holocellulose for Stable Carbon Isotope Analysis. 65:87-89.
- Leavitt, S.W. and Long A. (1989) Drought indicated in carbon-12/carbon-13 ratios in southwestern tree rings. *Water Res. Bull.* 25:341-347.
- Neilson R.P., King, G.A. and G. Koerper (1992) Toward a rule-based biome model. *Landscape Ecology* 7:27-43.
- Newberry, T.L. (1995) The Effect of Spatial & Temporal Variability on Water Relations in Pinyon Pine: I. Stomatal Response
- Newberry, T.L. (1995) The Effect of Spatial & Temporal Variability on Water Relations in Pinyon Pine: II. Whole Needle Response
- Noy-Meir, I. (1973) Desert Ecosystems: environment and producers. *Annual Review of Ecology and Systematics* 4:25-51.
- Sala, O.E., Lauenroth, W.K., Parton, W.J. and M.J. Trlica (1981) Water status of soil and vegetation in shortgrass steppe. *Oecologia* 48: 327-331.

Analysis of Change in Piñon-Juniper Woodlands Based on Aerial Photography, 1930's-1980's

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Bruce T. Milne
Peter Hraber

Abstract—We conducted an analysis of land cover change in selected piñon-juniper woodlands of New Mexico and Arizona, using aerial photographs from the 1930's through the 1980's. Both increases and decreases in woodland cover were observed. Fractal dimensions of woodland patches and cover-type changes were analyzed following the method of Krummel and others (1987). The analysis failed to identify the scale of anthropogenic disturbance, although land cover change is clearly due in part to human activity. The analytical method may be an insensitive indicator in these woodland systems because the fractal properties of both natural vegetative cover and human-induced changes are subject to topographic constraints.

Piñon-juniper woodlands are a common vegetation cover type in semi-arid regions of North America. In the southwestern United States, the association is typically composed of either *Pinus edulis* (Engelm.) Sarg. or *Pinus monophylla* Torr. & Frem. in conjunction with various species of *Juniperus*, most commonly *J. monosperma* (Engelm.) Sarg., *J. osteosperma* (Torr.) Little, or *J. scopulorum* Sarg. In Mexico, a variety of other piñon pine and juniper species can be important woodland components.

Various processes, both natural and anthropogenic, lead to changes in the spatial distribution of piñon-juniper woodlands over time. Important among these are (1) establishment of seedlings during periods of favorable climatic conditions, (2) mortality of seedlings or adult trees during drought conditions, (3) invasion of junipers into grassland in response to overgrazing and/or fire suppression, (4) removal of trees by humans as a result of fuelwood harvesting, chaining for rangeland management, or clearing of land for urban or agricultural uses.

One focus of landscape ecology is the development of quantitative techniques for the analysis spatial patterns and the changes in such patterns over time. Krummel and others (1987) used a perimeter-area scaling method to determine the fractal dimension of deciduous forest patches

in the lower Mississippi River floodplain of the United States. Their results showed a low fractal dimension (1.2) for small patches (<55.7 ha) with an abrupt transition to a higher fractal dimension (1.5) for larger patches (>100.4 ha). This was interpreted as indicating that anthropogenic processes play a dominant role in shaping small forest fragments, while natural processes subject to topographic constraints determine the shape of larger forested areas. On the basis of this result, Krummel and others (1987) suggested that the fractal dimension of vegetated patches could be monitored routinely as an indicator of landscape condition, with abrupt shifts to lower values indicating anthropogenic disturbance.

We have applied the method of Krummel and others (1987) to quantify patterns and changes in selected piñon-juniper woodlands of Arizona and New Mexico, USA. Using aerial photography, we calculated the fractal dimension of woodland patches at each study site at various times within a period extending from 1935 through 1988. Additionally, by comparing consecutive photographs, patches representing changes in land cover (i.e., loss or gain of woodland) could be delineated. We extended the methodology of Krummel and others by performing an analysis not only of the woodland patches themselves, but also patches representing changes in woodland cover over time. On the basis of our results, we find only equivocal support for the notion that the method can be used to routinely monitor anthropogenic disturbance in these landscapes. Our analysis points out several methodological issues which require more intensive study before the applicability of this technique to diverse landscape types can be properly assessed.

Materials and Methods

Four U.S. Geological Survey 1:24000 scale quadrangles were selected as study areas for this research. This is a subset of a set of approximately 30 study areas under investigation in a study of woodland/grassland ecotones (Milne and others 1996). The four quadrangles selected for the current analysis were chosen to represent a variety of climatic conditions, being arrayed along a longitudinal gradient of primarily winter precipitation in the west to a more bimodal pattern of winter and summer precipitation in the east. Panchromatic aerial photographs covering each quadrangle were obtained through the Earth Data Analysis Center at the University of New Mexico. Information on the locations of the quadrangles and the dates of the photography used is summarized in table 1.

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Table 1—Study areas and dates of aerial photography. Quadrangle names refer to U.S. Geological Survey 1:24000 maps.

Quadrangle name	Latitude	Longitude	Photograph dates
El Dado Mesa, NM	35° 22' 30"N	107° 22' 30"W	1935 1952 1988
Pine Canyon, NM	35° 15' 00"N	108° 07' 30"W	1935 1952 1987
Sandia Park, NM	35° 07' 30"N	106° 15' 00"W	1935 1951 1976 1987
Toothpick Ridge, AZ	36° 37' 30"N	112° 22' 30"W	1953 1981

Photographs were digitized using an 8-bit Hewlett Packard Scanjet IIc flatbed scanner at a resolution such that each individual pixel represented 2.5 x 2.5 m on the ground. Images were transferred from the original TIFF format to the VIFF format of the Khoros system (Konstantinos and Rasure 1994, Rasure and Williams 1991) and then to ASCII format for input to Grass 4.1 in which scanned images were mosaicked together and geographically rectified to the UTM coordinate system.

From imagery covering each 7.5 minute USGS quadrangle, a 1200 x 1200 pixel (3.0 x 3.0 km) subimage was extracted for analysis. The approximate position of the subimage within the quadrangle was determined randomly, by partitioning the quadrangle into four quadrants, and randomly determining the quadrant from which to extract the subimage. Exact location of the subimage was chosen by the analyst, with an effort made to minimize the inclusion of heavily shadowed areas within the subimage, since dark shadows can lead to errors in the subsequent classification.

The gray-scale subimages were classified into two classes corresponding to wooded areas and grasslands by interactively setting a gray-scale threshold and comparing the classified subimage to the original gray-scale subimage. This interactive procedure appeared to produce results which were as good or better than automatic classification schemes, such as k-means cluster analysis (Tou and Gonzalez 1974, p.94). A histogram equalization of the gray-scale was performed on some images to enhance their contrast prior to classification (Jensen 1996, p.150).

Changes in land cover were detected by overlaying classified subimages from successive dates. However, since successive images cannot be expected to be rectified with exact pixel-to-pixel accuracy, some allowance must be made to avoid falsely classifying slight mis-rectifications as actual changes in cover. This was done by defining a 4-pixel (10 m) wide buffer zone at each woodland/grassland interface. The buffer was created using a morphological edge detection algorithm, which involved convolution with a kernel defined to produce a two pixel thick external edge surrounding each woodland or grassland patch (Giardina and Dougherty 1988). Thus defined, the external edges of woodland and grassland patches adjoin, yielding a buffer four pixels in thickness.

Change in land cover was inferred only when a definitely classified pixel (i.e., outside the buffer) of one type (woodland or grassland) is definitely classified as the opposite type at a succeeding date. Overlays of the classified subimages (with buffer zone) produced maps of patches representing land cover change, both woodland converted to grassland and vice versa. Edge extraction and overlaying of subimages was done using the Khoros system (Konstantinos and Rasure 1994, Rasure and Williams 1991).

Fractal dimensions were calculated using a C program written by one of the authors (Johnson). Following the methodology of Krummel and others (1987), patches were ordered by size and regressions of log patch perimeter on log patch area were performed in a sliding window containing a constant number of patches, N. Separate regressions were performed for each possible window, ranging from the N smallest patches to the N largest patches. Krummel and others (1987) employed a window size of N = 200 patches. We performed regressions with window sizes of N = 50, 100, and 200 patches for each study area. The fractal dimension, D, was computed as two times the slope of the regression (Hastings and Sugihara 1993, pp.48-50, Lovejoy 1982).

Results

The amount of land surface showing a definite change in cover type is summarized in table 2 for each subimage at each time interval. The values in table 2 do not include any changes which occurred in the buffer zone of the patches defined in subimages, therefore, short distance (<10 m) shifts in patch boundaries will be undetected. Thus, the values in table 2 probably represent lower bounds on the area of land cover which changed over each time interval. Each subimage depicts an area of 900 ha. The areas exhibiting definite change in cover type over any given time interval comprise only a few percent of the total area in the subimage. The net effect of the changes can be either an increase or a decrease in woodland, depending upon the location and the time interval.

Patches of land surface which underwent a definite change in land cover showed a strongly skewed distribution of sizes,

Table 2—Land surface areas exhibiting definite change in subimages from each study site during each time interval. Positive values of net change represent an increase in woodland cover, negative values represent a decrease.

Study site	Time interval	Grassland to woodland	Woodland to grassland	Net change in woodland
El Dado Mesa	1935 - 52	15.0 ha	5.0 ha	+10.0 ha
	1952 - 87	15.2 ha	8.2 ha	+7.0 ha
Pine Canyon	1935 - 52	1.5 ha	3.6 ha	2.1 ha
	1952 - 86	7.3 ha	3.2 ha	+4.1 ha
Sandia Park	1935 - 51	16.1 ha	29.4 ha	13.3 ha
	1951 - 76	23.2 ha	5.0 ha	+18.2 ha
	1976 - 87	2.5 ha	20.3 ha	17.8 ha
Toothpick Ridge	1953 - 80	2.6 ha	16.4 ha	+13.8 ha

with many more small patches than large ones. For instance, in the Sandia Park subimage during the 1935-51 interval, the size of the patches representing land cover change ranged from 1 pixel (6.25 m²) up to 2631 pixels (16,400 m²), but with the median patch size near the lower end at 4 pixels (25 m²). Similar distributions were observed at other locations and at other intervals.

Sliding-window regressions were performed to evaluate the scale-dependence of the fractal dimension of woodland patches in all subimages. Only the 1935 Sandia Park subimage displayed a clear scale dependence (fig. 1a). The pattern was qualitatively similar to that observed by Krummel and others in their study: a low fractal dimension for small patches, with an abrupt shift to a higher dimension for large patches. However, most subimages displayed no clear shift in fractal dimension. The 1951 Sandia Park subimage is typical: the variation in estimates of D for small

patches is accompanied by a substantial drop in the R² of the regression, and thus cannot be interpreted as clear evidence for a scale-dependent shift in fractal geometry (fig. 1b).

Typical results of performing a sliding-window regression to compute the fractal dimension of the patches representing definite changes in land cover are presented in figure 2. As can be seen, the fractal dimension is relatively constant at a value of approximately 1.5, independent of mean patch size. This is true for both patches representing woodland converting to grassland, and vice versa. The only suggestion of a shift in the value of D is an increase for very small patch sizes (<75 pixels, i.e., <0.045 ha). However, the increasing values of D are accompanied by a decreasing R² for the regression model, indicating a poorer fit. The same pattern illustrated in figure 2 (namely, a constant D 1.5 except for a possible increase at small patch sizes) was evident at all study sites at all time intervals.

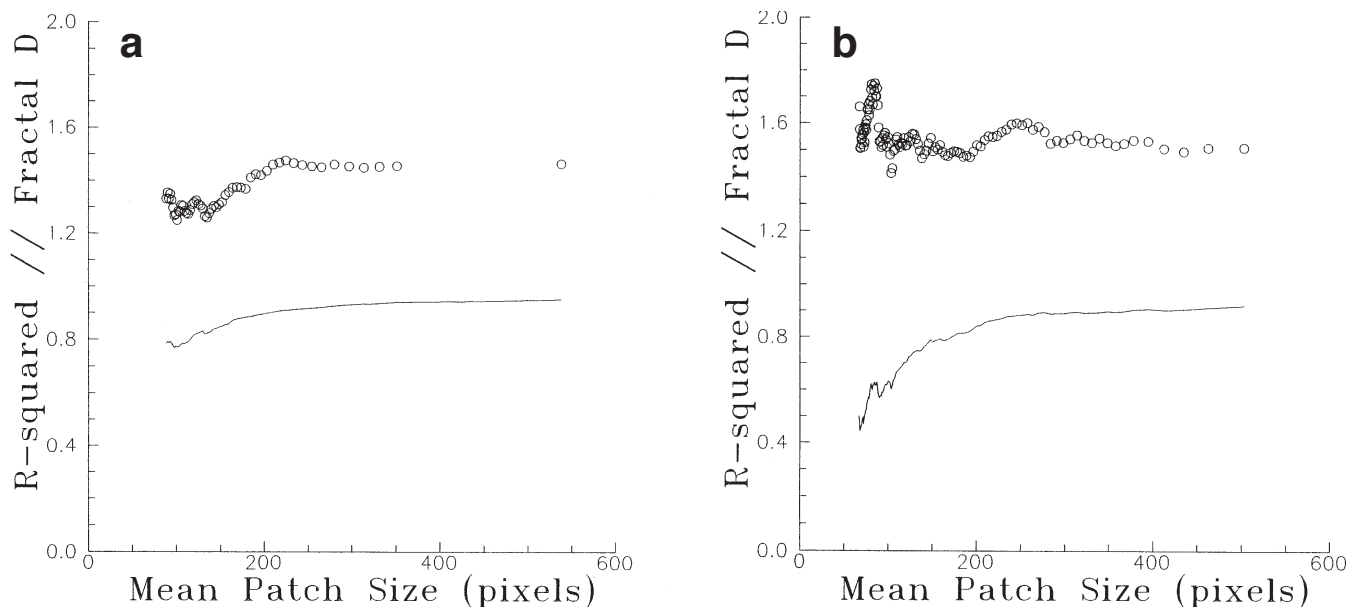


Figure 1—Upper curve: Fractal dimension as a function of mean patch size, computed using a sliding window of 100 patches. Lower curve: R² for each regression. Results are for the Sandia Park subimage. (a) woodland patches in 1935. (b) woodland patches in 1951.

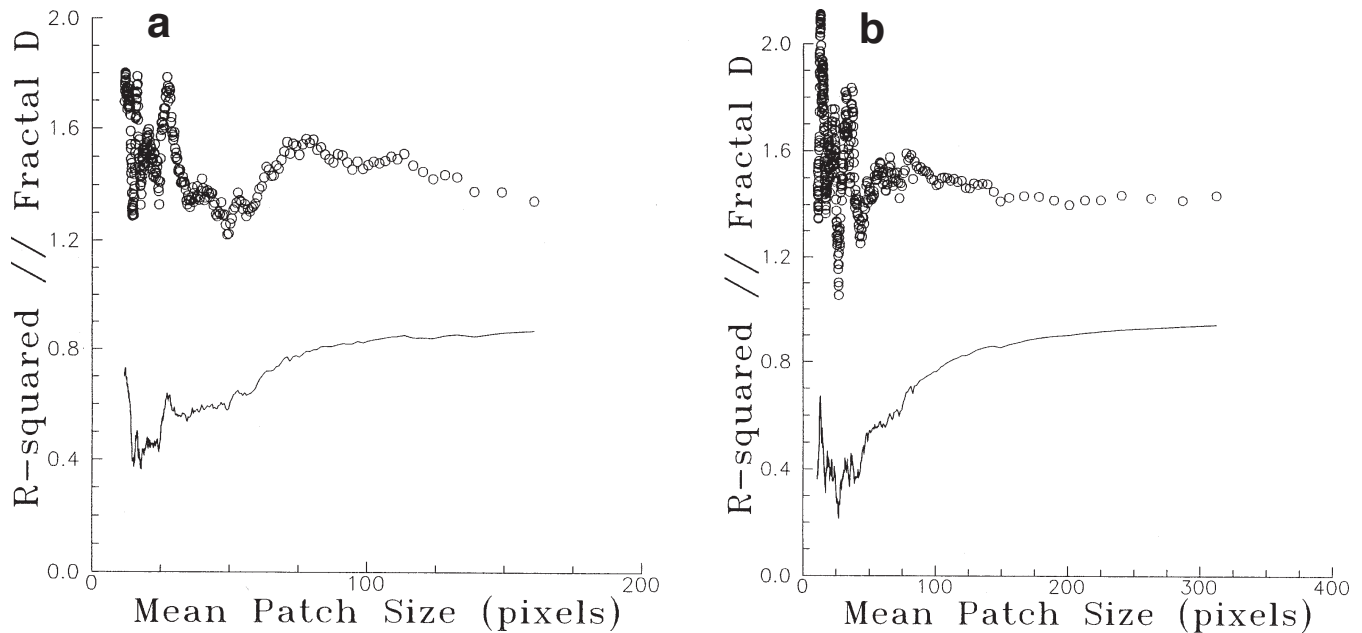


Figure 2—Upper curve: Fractal dimension as a function of mean patch size, computed using a sliding window of 100 patches. Lower curve: R^2 for each regression. Results are for the Sandia Park subimage during the interval from 1935 to 1951. (a) patches representing definite grassland converted to definite woodland. (b) patches representing definite woodland converted to definite grassland.

Discussion

The changes in cover over time presented in table 2 are consistent with a conceptual model of a slowly shifting mosaic of vegetation in the landscape (Pickett and White 1985, Remmert 1991, Watt 1947, Wu and Loucks 1995). On the time scale of decades, patches of former grassland are converted to woodland as conditions appropriate for juniper establishment are encountered, and conversely, patches of former woodland are lost as trees die due to natural causes or are removed by human activities. On a regional scale, piñon-juniper woodlands may be in a dynamic steady-state (*sensu* Bormann and Likens 1979) in which the proportion of the landscape covered by woodland is constant over time, except for stochastic fluctuations. Alternatively, there may be an overall increasing or decreasing trend in the amount of woodland cover, as the landscape adjusts to climatic trends and changes in human land use patterns. The data set used in this study is too small to distinguish between these alternatives. However, the methods developed here could be employed to address the issue. Resolution of this question would settle a long-standing debate.

When the fractal dimension of woodland patches is examined, the usual pattern observed was a value in the range of 1.5-1.6, with larger fluctuations (and low R^2) at small patch sizes. Only in the case of the 1935 Sandia Park subimage was there a pattern consistent with a systematic shift in fractal dimension as a function of mean patch size. Visual inspection of the original gray-scale images strongly suggests that anthropogenic disturbance occurs in other subimages, but such disturbance is not detectable on the basis of a routine application of the method of Krummel and others (1987).

Extension of the method to analyze patches representing changes in woodlands between successive photographs did not improve our ability to detect anthropogenic disturbance. In all such analyses, the fractal dimension appeared relatively constant with a value near 1.5. The only observed fluctuations occurred at very small patch sizes. However, these fluctuations were always accompanied by substantial reductions in the R^2 of the regression, indicating a lack of conformity to the power-law scaling, thereby making any interpretation difficult.

One bias that might affect our estimation of fractal dimensions, particularly at small patch sizes, is an effect discussed by Milne (1990). When fractal dimensions are calculated from a perimeter to area ratio, the maximum value for any possible arrangement of N pixels varies in a sawtooth pattern as a function of N , and is often below the theoretical maximum of 2.0. This effect is most pronounced when N is small. In a test of the impact of this bias on our results, we calculated a normalized fractal dimension as follows:

$$D_{\text{norm}} = 2(D/D_{\text{max}})$$

where D_{norm} is the normalized fractal dimension, D is the fractal dimension from the usual perimeter-area relationship, and D_{max} is the maximum fractal dimension for any arrangement with the same number of pixels as the given cluster. Note that the normalized fractal dimension will always have maximum value of 2.

As expected, the greatest effect of this adjustment was at small patch sizes. However, over the range of patch sizes used in our analyses, the effect was not large, and did not qualitatively change the nature of the graphs of fractal dimension vs. mean patch size. Specifically, fluctuations in

the graph at small patch sizes which were evident when the usual fractal dimension was plotted were still evident when the normalized fractal dimension was used (data not shown). If anything, the amplitude of the fluctuations was somewhat greater when the normalized fractal dimension was employed. Since the normalized fractal dimension did not change the interpretation of our results, only data based on the usual definition of fractal dimension were presented here.

The fact that the fractal dimensions of both the woodland patches and the patches representing change hover near a value of 1.5 is suggestive. Topographic surfaces, particularly mountainous areas such as our study sites, typically have a fractal dimension $D_{\text{surface}} = 2.5$ (Mandelbrot 1983). If piñon-juniper woodlands were restricted to elevations above some fixed threshold, one would expect the resulting pattern to have a fractal dimension $D_{\text{woodland}} = D_{\text{surface}} - 1 = 1.5$. Of course, in the real world, slope and aspect effects modify the lower elevational ecotone of piñon-juniper woodlands, but these effects may not change the fractal dimension much. Thus, the fact that most patches have fractal dimensions near 1.5 is consistent with the hypothesis that the distribution of woodlands, and changes in woodlands, are strongly constrained by topography.

It may be reasonable to assume that even the patterns of anthropogenic disturbance in these ecosystems may be largely determined by topographic constraints. The Mississippi floodplain forests analyzed by Krummel and others (1987) were probably essentially continuous prior to human disturbance. Thus, any edges arising from human activity are likely to be simple in shape, and to leave fragments with low fractal dimension. Piñon-juniper woodlands in mountainous terrain, on the other hand, are fragmented in their natural condition. Human activity may result in the removal of patches, or parts of patches, of woodland. Yet even in a highly disturbed piñon-juniper system, most of the edges would still be topographically influenced. This effect is due to a combination of (1) the large number of natural edges controlled by topography, and (2) the tendency of human removal of trees to follow elevational contours when there is substantial topographic relief. Because both natural processes and human activities are influenced by topography, a shift in fractal dimension may not occur.

Although topographic constraints could account for the difference between our results and those of Krummel and others (1987), there are several methodological problems that might also have influenced our results or their interpretation. First, our results could be influenced by errors in the initial classification of the gray-scale images into woodland and grassland cover types. Most problematic are probably shadows, since the true vegetation cover in heavily shadowed areas cannot be ascertained, and dark areas of shadowed grassland may be misclassified as woodland. Shadows are most pronounced in areas of high topographic relief, and the degree of shadowing and positions of the shadows may change from photograph to photograph depending upon the season and time of day. Thus, shifts in shadows could be misinterpreted as changes in woodland.

The second potential source of error is mis-rectification of the images between dates. If there is mis-rectification, the patches in one image will be shifted in position relative to

their location in the other image. A change map computed from such mis-rectified data will show many falsely identified changes outlining the perimeters of all the patches. Such an effect is visually apparent if change maps are computed without first defining a buffer zone. However, with the 10 m buffer zone, such outlining of all patches is no longer apparent. Thus, we conclude that the buffer used in this study is sufficient to eliminate most or all of the false inferences of change due to mis-rectification.

Finally, our computation of the fractal dimension of clusters could be affected by the use of the morphological algorithm used to define the buffer. The morphological algorithm essentially expands the width of the interface between woodland and grassland patches. In so doing, the perimeters of the remaining clusters may tend to smoothed, and this effect might be most noticeable for small patches. If so, the fractal dimension of patches after the buffer is defined should be lower than their original fractal dimension, with small patches being particularly affected.

The work of Krummel and others (1987) is frequently cited as an example of human impact on landscape pattern, but few other studies have applied the same methodology. Perimeter-area relationships are frequently used to compute fractal dimensions in analyses of landscape pattern, but the dependence on mean patch size is usually not examined (for example, O'Neill and others 1988, Turner 1990). Some papers have employed modifications of the Krummel and others (1987) methodology. For instance, Turner and others (1991) describe a method they call the "variance staircase" which is related to a fractal dimension. Meltzer and Hastings (1992) employed "rolling regressions" to calculate the size-related fractal properties of grass patches in a rangeland in Zimbabwe, based on fit to a hyperbolic size distribution. Vedyushkin (1994) reported scale-dependent fractal dimensions for remotely-sensed data (normalized difference vegetation index, NDVI, and thermal infrared radiation, TIR) for a forest in central Russia, based on a box-counting procedure. Although these studies can be viewed as generally supportive of the hypothesis that landscape patches display size-related shifts in their fractal dimension, they do not constitute independent support for the specific methodology of Krummel and others (1987). Krummel and others (1987) suggest that their "technique should be of particular interest to the analysis of remotely sensed data, as it provides a simple metric, D , that indicates the scale at which processes are occurring on the ground." However, the published evidence for such utility is still appears to be based on the analysis of a single map representing one portion of the Mississippi floodplain.

Our results, based on applying the methodology of Krummel and others (1987) to piñon-juniper woodlands in the southwestern United States, raise questions about the general utility of the method for detection of anthropogenic disturbance. The possibility must be considered that scale-dependent variations in the fractal dimension of patches may only serve as good indicators of certain types of anthropogenic disturbance, or may only be useful in certain landscapes. Further investigation is needed to determine the scope over which this methodology can be routinely used to detect anthropogenic disturbance.

Acknowledgments

We thank T.F.H. Allen for his insightful comments on a poster presentation of our results. This research was supported by USDA Forest Service, Rocky Mountain Research Station, Albuquerque, NM through Cooperative Agreement No. 28-C4-880 to Drs. Johnson and Milne.

References

- Bormann, F.H.; Likens, G.E. 1979. Catastrophic disturbance and the steady state in northern hardwood forests. *American Scientist* 67:660-669.
- Giardina, C.R.; Dougherty, E.R. 1988. *Morphological Methods in Image and Signal Processing*. Prentice-Hall, Englewood Cliffs, NJ.
- Hastings, H.M.; Sugihara, G. 1993. *Fractals: A User's Guide for the Natural Sciences*. Oxford Univ. Press, Oxford, England.
- Jensen, J.R. 1996. *Introductory Digital Image Processing: A Remote Sensing Perspective*. 2nd ed. Prentice Hall, Upper Saddle River, NJ.
- Konstantinos, K.; Rasure, J.R. 1994. The Khoros software development environment for image and signal processing. *IEEE Trans. Image Processing* 3:243-252.
- Krummel, J.R.; Gardner, R.H.; Sugihara, G.; O'Neill, R.V.; Coleman, P.R. 1987. Landscape patterns in a disturbed environment. *Oikos* 48:321-324.
- Lovejoy, S. 1982. Area-perimeter relation for rain and cloud areas. *Science* 216:186-187.
- Mandelbrot, B.B. 1983. *The Fractal Geometry of Nature*. W.H. Freeman, New York.
- Meltzer, M.I.; Hastings, H.M. 1992. The use of fractals to assess the ecological impact of increased cattle population: case study from the Runde Communal Land, Zimbabwe. *Journal of Applied Ecology* 29:635-646.
- Milne, B.T. 1990. Lessons from applying fractal models to landscape patterns. In: M.G. Turner and R.H. Gardner (eds.) *Quantitative Methods in Landscape Ecology*, Springer-Verlag, Berlin.
- Milne, B.T.; Johnson, A.R.; Keitt, T.H.; Hatfield, C.A.; David J.; P. Hrabar, P. Detection of critical densities associated with piñon-juniper woodland ecotones. *Ecology* 77:805-821.
- O'Neill, R.V.; Krummel, J.R.; Gardner, R.H.; Sugihara, G.; Jackson, B.; DeAngelis, D.L.; Milne, B.T.; Turner, M.G.; Zygmunt, B.; Christensen, S.W.; Dale, V.H.; Graham, R.L. 1988. Indices of landscape pattern. *Landscape Ecology* 1:153-162.
- O'Neill, R.V.; Gardner, R.H.; Milne, B.T.; Turner, M.G.; Jackson, B. 1991. Heterogeneity and spatial hierarchies. In: *Ecological Heterogeneity*, J. Kolasa and S.T.A. Pickett (eds.) Springer-Verlag, Berlin. pp.85-96.
- Pickett, S.T.A.; White, P.S. (eds.). 1985. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, San Diego, CA.
- Rasure, J.R.; Williams, C.S. 1991. An integrated data flow visual language and software development environment. *J. Visual Languages and Computing* 2:217-246.
- Remmert, H. (ed.). 1991. *The Mosaic-Cycle Concept of Ecosystems*. Springer-Verlag, Berlin, Germany.
- Tou, J.T.; Gonzalez, R.C. 1974. *Pattern Recognition Principles*. Addison-Wesley, Reading, MA.
- Turner, M.G. 1990. Spatial and temporal analysis of landscape patterns. *Landscape Ecology* 4:21-30.
- Turner, S.J.; O'Neill, R.V.; Conley, W.; Conley, M.R.; Humphries, H.C. 1991. Pattern and scale: statistics for landscape ecology. In: *Quantitative Methods in Landscape Ecology*, M.G. Turner and R.H. Gardner (eds.), Springer-Verlag, Berlin. pp.17-49.
- Vedyushkin, M.A. 1994. Fractal properties of forest spatial structure. *Vegetatio* 113:65-70.
- Watt, A.S. 1947. Pattern and process in the plant community. *Journal of Ecology* 35:1-22.
- Wu, J.; Loucks, O.L. 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. *Quarterly Review of Biology* 70:439-466.

Applications for Predicting Precipitation and Vegetation Patterns at Landscape Scale Using Lightning Strike Data

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Abstract—Previous publications discussed the results of my dissertation research on relationships between seasonality in precipitation and vegetation patterns at landscape scale. Summer precipitation at a study site in the Zuni Mountains, NM, was predicted from lightning strike and relative humidity data using multiple regression. Summer precipitation patterns were mapped using a Geographic Information System (GIS). Winter precipitation and vegetative cover were obtained from the Terrestrial Ecosystem Survey (TES). Finally, winter and summer precipitation amounts and their percent of annual precipitation were compared to grass and tree cover. Results indicated that winter precipitation influenced tree cover. Grass cover dominated by *Bouteloua gracilis* was most closely related to summer precipitation. Grass cover dominated by *Festuca arizonica* was most closely related to winter precipitation. This manuscript presents a synthesis of the dissertation research. It discusses how land managers can use lightning strike data and TES information. Ecosystem management applications for predicting precipitation and vegetation patterns at landscape scale are explored. For example, vegetation regeneration may be more successful if precipitation patterns are known. Understanding relationships between vegetation and precipitation patterns can also be used to assess the behavior of fire and for restoring disturbed areas. Additional research at landscape scale could improve our understanding of potential changes in vegetation patterns due to climatic warming.

Study Site and Methods

In New Mexico, 50-70 percent of the annual precipitation comes from convective thunderstorms in the months of June through September. This precipitation has high spatial variability that may not be detected by conventional precipitation monitoring stations. It can be accurately estimated using lightning strike data with a spatial resolution of about 2 km, and the method is appropriate for landscape scale (Gosz and others 1995).

Lightning direction finders detect cloud-to-ground lightning that is in progress. The instruments sense low-frequency radio pulses associated with lightning discharges. Lightning

sensors are operated throughout the United States by Global Atmospheric, Inc. as part of a National Lightning Detection Network. Gosz and others (1995) developed algorithms between lightning and summer precipitation quantity to determine rainfall depth and distribution at the Sevilleta National Wildlife Refuge, NM. These methods were later applied to a 140 km² site (Pole Canyon) in the west Rio San Jose watershed near Grants, New Mexico (Potter 1996; Potter and Gorman 1996; Potter and others, in press). This study site was a prototype for ecosystem management located within the Mt. Taylor Ranger District of the Cibola National Forest.

First, summer precipitation was predicted from lightning strike and relative humidity data using multiple regression. Then summer precipitation patterns were mapped using a geographic information system (GIS). Winter precipitation and vegetative cover were obtained from the Terrestrial Ecosystem Survey (TES) of the Forest Service Southwestern Region (USDA Forest Service 1986). Finally, winter and summer precipitation amounts and their corresponding percent of annual precipitation were compared to grass and tree cover using modeling capabilities within the ARC/INFO Geographic Information System.

Both precipitation and vegetation data were ranked and divided into three classes. Map overlay and cross-tabulation techniques were used to compute percent composition of vegetation classes within each precipitation class. Relationships between precipitation and vegetation by growth form (for example, trees and grass) were tested using Cramer's V statistic, a measure of association. Results indicated that winter precipitation influenced tree cover. Grass cover dominated by *Bouteloua gracilis*, a warm-season species, was most closely related to summer precipitation. Grass cover dominated by *Festuca arizonica*, a cool-season species, was most closely related to winter precipitation.

These results were consistent with findings by Phillips and Ehleringer (1995) that winter precipitation reaches deep soil layers and is subsequently utilized by tree roots while summer rains have minimal uptake by trees. Other factors that can affect vegetation patterns were also discussed in the dissertation. The following discussion focuses on applications of these research results and related studies.

Discussion

Gosz and others (1995) noted that contour plots of precipitation generated from lightning data could be combined with satellite data for vegetation, i.e., a greenness index, to identify areas that will have short-term increases in primary production of terrestrial vegetation. Knowledge of precipitation patterns could be used to maximize the

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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effectiveness of restoration projects such as reseeding or sludge application. For example, degraded areas that recently received a high intensity of lightning strikes could be targeted for immediate restoration. Improved timing of the project could lead to greater success in the germination, growth and survival of seeded plants. Hogg and Schwarz (1997) investigated conifer regeneration across a moisture gradient from semi-arid to moderately moist climates. They found that regeneration capacity was related to a climatic moisture index.

Patterns in precipitation and vegetation could also be used to help determine desired livestock stocking rates and timing or to evaluate existing livestock management practices. Oesterheld and others (1998) determined relationships at regional scale between stocking rates and the normalized-difference vegetation index-integrated value (NDVI-I) obtained from advanced very high resolution radiometer (AVHRR) data. AVHRR data are used to estimate aboveground net primary productivity. Although the remote-sensing method was applied at regional scale, it could be adapted to predict stocking rates at regional scale, landscape scale, and for areas within a landscape. Variations in soil moisture, soil quality and other factors are also important in selecting or evaluating livestock management alternatives.

Lightning strikes are the primary cause of natural fire ignitions. Latham and others (1997) combined lightning location data and fire risk data (ignition potential based on fuel maps) to estimate probable fire occurrence. Predictions were compared to the sole use of lightning data and the National Fire Danger Rating System to assess wildfire potential. Results were better than using lightning strikes alone since some fires are short duration or fail to spread after ignition. Combining Latham's techniques with those of Gosz and others (1995) could improve wildfire predictions by accounting for the spatial variability in precipitation. Results could enhance the benefits of savings in fire suppression time and cost, and reduced risk to firefighter safety.

Climate effects on the growth of individual trees and species can be derived at fine spatial scales from statistical relationships between ring widths and monthly total precipitation and monthly mean temperature. Relationships between trees and precipitation will vary among species, and results of this investigation were similar to ring-width studies of conifers. Meko and others (1994) reconstructed amounts of cool-season precipitation from ring-width indices of conifers in the Sonoran Desert that are drought-sensitive. They also analyzed the relationship between summer precipitation and ring-width components formed before and after the summer rainy season began. Results showed no relationship between summer rainfall and total ring width. Growth was strongly related to winter precipitation. However, a relationship with summer precipitation was detected in the late-growth component of separated ring widths.

Any application of the research for ecosystem management needs to be framed in an ecological context. According to the Ecological Society of America's Committee on the Scientific Basis for Ecosystem Management (Christensen and others 1996) "ecosystem management is management driven by explicit goals, executed by policies, protocols, and practices, and made adaptable by monitoring and research

based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem structure and function." The following seven components are essential:

"1. long-term sustainability as fundamental value; 2. clear, operational goals; 3. sound ecological models and understanding; 4. understanding complexity and interconnectedness; 5. recognition of the dynamic character of ecosystems; 6. attention to context and scale; 7. acknowledgment of humans as ecosystem components; and 8. commitment to adaptability and accountability." Products from the dissertation study contribute to ecological modeling at landscape scale and our understanding of ecological complexity and the dynamic character of ecosystems.

TES Applications

The Southwestern Region's Terrestrial Ecosystem Survey for classifying and mapping terrestrial ecosystems is a valuable source of soil, climate and vegetation data. A secondary benefit of the lightning research was to explore a new application for TES data. More recently, the practicality of using TES data as input variables to predict fire behavior was investigated by Mark Grupe.

In Grupe's study (1998) the FARSITE model for predicting fire growth (Finney 1993) was applied to a prescribed fire planned at Barranco Canyon within the Cibola National Forest, Mountainair District. Data for tree height and canopy cover were direct inputs for FARSITE while crown base height and crown bulk density were interpreted from the TES. A Geographic Information System was used to handle data and for spatial modeling. Management applications of TES data and GIS will likely increase with time due to their ability to help address complex ecosystem issues.

Applications for Lightning Data

Lightning direction finders are one of several remote sensing methods to locate lightning and understand thunderstorm activity. A Lightning Detection and Ranging (LDAR) system has been developed to detect and locate VHF radiation emitted by lightning strikes (Forbes 1993). In addition to other types of ground-based systems, there are space-based precipitation radar systems and lightning detectors in geostationary orbit.

NASA plans to measure tropical rainfall using a space-based precipitation radar system. It's designed to provide high resolution, 3-D images of rainfall distributions and intensity over land and ocean. This Tropical Rainfall Measuring Mission (TRMM) will also provide information on cloud cover, type, and temperatures and radiative energy that is emitted and reflected from the Earth. A Lightning Imaging Sensor (LIS) associated with the TRMM Observatory will be used to study the global occurrence of lightning and its relationship to precipitation (Christian and McCook 1997). Resolution is 5-10 km with coverage over a large portion of the Earth's surface. These data can help quantify associations between tropical rainfall and global circulation of the atmosphere.

A Lightning Mapper Sensor from geostationary orbit will continuously map lightning discharged during day and

night at a storm-scale spatial resolution. It will detect and locate discharges from both cloud-to-ground and intra-cloud lightning over large portions of the Earth. The data will be available in real-time for severe storm detection and warning, convective rainfall estimates and storm tracking. Another potential use is to improve long-term weather forecasting.

Applications for predicting relationships between climate and lightning vary by spatial scale. For example, Williams (1992, 1994) developed a method to analyze global temperatures from lightning flashes and subsequent changes in the amplitude of Schumann resonances associated with the earth's electromagnetic field. Methods developed by Gosz and others (1995) and refined by Potter and others (in press) are appropriate at the landscape scale. The National Weather Service (NEXRAD) radar system detects precipitation intensities within thunderstorms. Using surface observations, estimates of precipitation volume could be calibrated from the radar data. Thus, in the future Doppler radar could be used to quantify precipitation amounts at fine spatial scales.

Conclusions

In the dissertation study, canopy cover for grasses and trees was a function of seasonal precipitation. Vegetation measures vary and can be related to several factors. For example, Walker and Langrige (1997) found that the best indicator for grass biomass rates in Australian savannas was an index that incorporated subsoil and topsoil moisture. Similarly, Iverson and others (1997) used an integrated moisture index to predict forest productivity and species composition at dry versus mesic sites. Although average climate conditions were used in this study, climatic extremes can also be essential factors for vegetation patterns. Various factors affecting vegetation pattern were presented as alternate hypotheses in the dissertation.

Knowing how vegetation patterns are related to precipitation patterns at landscape scale can be useful in fire management, ecosystem restoration projects, and ecosystem management. Such information could be used to improve wildfire predictions and staffing plans. Degraded areas that recently just received a high intensity of lightning strikes could be targeted for immediate restoration projects such as reseed-ing or sludge application. Patterns in precipitation and vegetation could also help determine livestock stocking rates and timing, or be used to evaluate existing management practices. Understanding how the distribution of grasses and trees changes in response to precipitation and other climate variables might help managers determine whether desired plant distributions can be achieved and sustained.

In addition to management applications, there are potential research applications from the study. The modeling capabilities of ARCINFO could be used to help predict migration patterns of trees and grasses at landscape scale in response to various climate change scenarios. Anticipated improvements in wildland fire assessment by combining Latham's techniques with those of Gosz and others (1995) would require additional investigation or collaboration.

Acknowledgments

The initial research was funded by Cooperative Agreement No. 28-C4-810 between the University of New Mexico Department of Biology and the USDA Forest Service Rocky Mountain Research Station. I am grateful for that research opportunity through the Rio Grande Basin grant administered by Dr. Deborah Finch and in cooperation with the Sevilleta Long Term Ecological Research site (LTER). Access to UNM facilities and assistance from LTER staff are appreciated.

References

- Christensen, N.L., A.M. Bartuska, J.H. Brown, S. Carpenter, C. D'Antonio, R. Franics, J. F. Franklin, J.A. MacMahon, R.F. Noss, D.J. Parsons, C.H. Peterson, M.G. Turner and R.G. Woodmansee. 1996. The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications* 6(3):665-691.
- Christian, H.J. and M.A. McCook. Lightning detection from space (a lightning primer). Global Hydrology and Climate Center. Internet WWW page, at URL: <http://www.ghcc.msfs.nasa.gov/liisotd.html> (last updated 12 Feb. 1997).
- Finney, 1993. Modeling the spread and behavior of prescribed natural fire. pp. 138-143 IN *Proceedings of the 12th International Conference on Fire and Forest Meteorology*. Society of American Foresters, Bethesda.
- Forbes, G.S. 1993. Lightning studies using LDAR and LLP data and applications to weather forecasting at Kennedy Space Center. National Aeronautics and Space Administration CR-194678. pp. 165-194.
- Gosz, J.R., D.I. Moore, H.D. Grover, W. Rison and C. Rison. 1995. Lightning estimates of precipitation location and quantity during convective thunderstorms on the Sevilleta Long Term Ecological Research (LTER) site in New Mexico. *Ecological Applications* 5(4):1141-1150.
- Grupe, Mark. 1998. Assessing the applicability of the Terrestrial Ecosystem Survey for FARSITE. Masters thesis. University of New Mexico, Department of Geography, Albuquerque.
- Hogg, E.H. and A.G. Schwarz. 1997. Regeneration of planted conifers across climatic moisture gradients on the Canadian prairies: implications for distribution and climate change. *Journal of Biogeography* 24:527-534.
- Iverson, L.R., M.E. Dale, C.T. Scott and A. Prasad. 1997. A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (U.S.A.). *Landscape Ecology* 12:331-348.
- Latham, D., R. Burgan, C. Chase and L. Bradshaw. 1997. Using Lightning Location in the Wildland Fire Assessment System. Gen. Tech. Rep. INT-GTR-349. Ogden, UT. USDA Forest Service, Intermountain Research Station, 5 p.
- Meko, D., T.W. Swetnam, C. Woodhouse, and C. Baisan. 1994. Climatic variation in the Sonoran Desert from instrumental climate data and tree rings. Annual progress report - year 2. Submitted to National Park Service, SODE Biogeographical Region. Laboratory of Tree-Ring Research, University of Arizona, Tucson.
- Oosterheld, M., C.M. DiBella and H. Kerdiles. 1998. Relation between NOAA-AVHR satellite data and stocking rate of rangelands. *Ecological Applications* 8(1):207-212.
- Phillips, S.L., and J.R. Ehleringer. 1995. Limited uptake of summer precipitation by bigtooth maple (*Acer grandidentatum* Nutt) and Gambel's oak (*Quercus gambelii* Nutt). *Trees* 9:214-219.
- Potter, D.U., J.R. Gosz, M.C. Molles, Jr. and L.A. Scuderi. 1998. Lightning, precipitation and vegetation at landscape scale. *Landscape Ecology*, in press.
- Potter, D.U. 1996. Spatial relationships among lightning, precipitation and vegetative cover in watersheds of the Rio Puerco Basin. Doctoral dissertation. University of New Mexico, Department of Biology, Albuquerque.

- Potter, D.U. and S.M. Gorman. 1996. Spatial relationships among lightning, precipitation and vegetative cover in watersheds of the Rio Puerco Basin. pp. 113-127 In: Proceedings of the Riparian Symposium, Sept. 18-22, 1995, Albuquerque. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. General Technical Report RM-GTR 272.
- United States Department of Agriculture, Forest Service. 1986. Terrestrial Ecosystem Survey Handbook. Southwestern Region. USDA Forest Service, Albuquerque.
- Walker, B.H. and J.L. Langrige. 1997. Predicting savanna vegetation structure on the basis of plant available moisture (PAM) and plant available nutrients (PAN): a case study for Australia. *Journal of Biogeography* 24:813-825.
- Williams, E.R. 1992. The Schumann resonance: a global tropical thermometer, *Science* 256: 1184-1187.
- Williams, E.R. 1994. Schumann resonance measurements as a sensitive diagnostic for global change. National Institute for Global Environmental Change, Annual Report, July 1, 1993+June 30, 1994, p. 146.

Restoration and Monitoring Issues



Trial by Fire: Restoration of Middle Rio Grande Upland Ecosystems

Samuel R. Loftin

Abstract—The majority of upland ecosystems (desert scrub, grassland, pinyon-juniper, ponderosa pine and higher elevation conifer forests) in the Middle Rio Grande Basin were historically dependent on periodic fire to maintain their composition, productivity, and distribution. The cultural practices of European man have altered the function, structure, and composition of virtually all Middle Rio Grande Basin ecosystems. Centuries of widespread livestock grazing has altered natural fire frequencies and intensities in upland habitat types. Fire suppression has led to an increase in woody plant abundance on many upland sites, from grassland to ponderosa pine forests. The negative consequences range from increased surface runoff and soil erosion in grasslands, shrublands and pinyon-juniper woodlands to increased potential for severe wildfire in ponderosa pine forests. The goal of restoration in these systems is to reintroduce fire. Unfortunately, due to varying levels of degradation, it may not be possible, or reasonable, to simply burn areas and expect them to recover their former attributes. Successful restoration requires some knowledge of the extent of degradation and the potential for recovery. I will discuss the process of identifying problems, determining land status, and defining realistic objectives. I will present three case studies as examples of ecosystems in different stages of degradation that required different restoration procedures for reintroduction of fire.

Ecological restoration is defined as the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes and structures, regional and historical context, and sustainable cultural practices (The Society for Ecological Restoration). Restoration of Middle Rio Grande upland ecosystems generally involves reintroduction of fire. Restoration of some systems may begin with a prescribed fire, however, other systems have changed to the point that additional treatments are necessary before fire can be used. An understanding of ecosystem disturbance dynamics and their potential to create problems, as well as the health and status of the system in question, can help to determine appropriate procedures for ecosystem restoration or to prioritize multiple restoration projects given limitations of time and resources. Monitoring programs must be implemented to provide the data necessary to make objective evaluations of the consequences of disturbance and ecosystem status.

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Problem Identification

It is important to understand the difference between disturbances and problems. A disturbance can change any combination of the functional, structural, or compositional components of an ecosystem. The change may be temporary or permanent. The change is not necessarily detrimental to the health of the ecosystem. Certain disturbances, such as fire or flooding, are critical to the long-term maintenance of grassland and riparian ecosystems, respectively.

The changes brought about by disturbance may result in a problem or they may not. From a purely ecological standpoint, this is dependent upon the response (the resistance and resilience) of the ecosystem in question and the magnitude and intensity of the disturbance. But in large part the perception of a problem is dependent upon the values and judgment of the person or persons managing the land. Although the perception of a problem will always be somewhat subjective, it should be possible to identify ecosystem indicators that can be objectively quantified and monitored. Problems could be more objectively defined as one or more indicator values occurring outside of some range of acceptable variation. Possible ecological indicators might include components of ecosystem function (surface runoff, soil erosion, fire/flood occurrence and frequency) and ecosystem composition and structure (invasive native and exotic plants, threatened and endangered species). Social and economic indicators could also be developed and incorporated into the analysis.

Ecosystem Status

Ecosystem status can be conceptualized using a state and transition model (fig. 1) such as the Rangeland Health Model proposed by the National Research Council Committee on Rangeland Classification (Busby and others 1995, CRC 1994). In this model, ecosystems are classified as healthy, at risk, and unhealthy. A healthy ecosystem can sustain the stability of soils, watersheds and ecological processes and the capacity to produce commodities and satisfy values. An ecosystem at-risk shows signs of degradation and has an increased vulnerability to further degradation but ecological processes can still be used to restore the system within a time frame meaningful to humans. An unhealthy ecosystem has been degraded to the point that improvement cannot occur without external inputs such as seeding, soil amendments, thinning, etc. The circles with letters represent a range of ecosystem states within these health classifications. The vertical axis represents biological potential or the capacity to produce commodities and satisfy values (CRC 1994). The vertical dashed lines represent thresholds between ecosystem states. Using

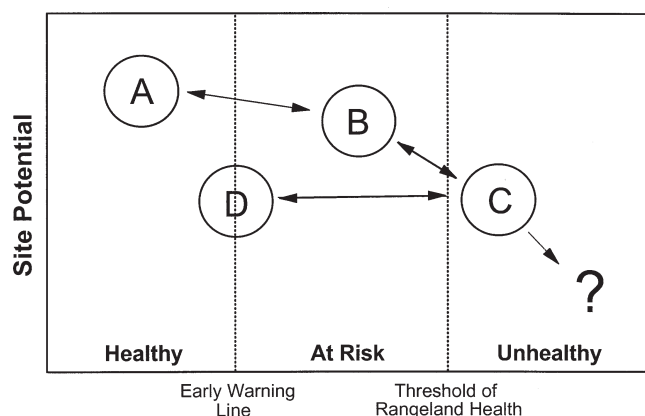


Figure 1—Rangeland health model adapted from a report by the National Research Council Committee on Rangeland Classification (1994) and Busby and others (1995).

a typical grassland degradation scenario, the state represented by circle A would be a healthy, productive grassland or grassland savanna ecosystem. Disturbances such as grazing and fire suppression can lead to problems like woody plant encroachment and a reduction in herbaceous plant abundance which may indicate that the first threshold (early warning line) has been crossed and the original grassland is at risk (circle B). Removal of grazing pressure and reintroduction of fire could halt the degradation process and initiate restoration. Continued disturbance could lead to further reductions in herbaceous ground cover with significant increases in surface runoff and soil erosion which would indicate that the second threshold (threshold of rangeland health) has been crossed. At this point (circle C) a positive feedback cycle of increasing degradation has been initiated and the system is no longer under biological control. Consequently, ecological processes alone cannot be used to restore the system within a time frame meaningful to humans. If no action is taken the system will continue to degrade (?) and/or eventually stabilize as a new vegetation assemblage at a much reduced biological potential (circle D).

Realistic Objectives

The ability to distinguish between disturbances and the problems they create, and determine ecosystem status will provide insight into what types of restoration procedures will be most effective and where limited resources will best be used. Burning an unhealthy degraded woodland is not likely to restore a grassland. Either additional measures must be taken or resources should be used on at-risk sites that have a greater potential for recovery. Conversely, fertilizing and reseeding an at-risk site may be unnecessary if equally beneficial results can be obtained at a much lower cost by burning.

Role of Monitoring

Monitoring is critical to the success of this process. Data from indicators are necessary to quantify the effects of

disturbance, objectively identify problems, and determine ecosystem status. All too often, this research included, few to no data are available to make these pretreatment evaluations and we must rely on a subjective evaluation of the site. Once a course of action has been determined, data are critical to objectively evaluate treatment effects and progress toward management objectives.

There are two basic types of monitoring programs. The first, a general or baseline monitoring program, can be used to identify changes in ecosystem indicators but cannot be used to determine the cause of these changes. In order to attempt to determine cause and effect a specialized or research monitoring design must be used which involves monitoring on treated sites as well as untreated control sites.

There are pros and cons to both forms of monitoring. Although cause and effect cannot be determined with a baseline monitoring program, it is a much more cost effective method for monitoring at broad scales. In this age of adaptive management, we should be using an adaptive monitoring approach with baseline monitoring applied at broad scales to detect changes in ecosystem indicators. If a change in an indicator is determined to be a problem, or a potential problem, a specialized monitoring design could be implemented at a finer scale to determine the cause of the problem and help determine the appropriate management response.

Case Studies

The following case studies of restoration of former grassland ecosystems in various stages of degradation are used as examples of the process described above. In each case the treatments and objectives change depending upon the problems and ecosystem status.

The Albuquerque Open Space (AOS) site is a healthy bunchgrass grassland located west of Albuquerque near the Double Eagle Airport. The site is dominated by Indian ricegrass, *Oryzopsis hymenoides* (Roem. & Schult.) Ricker, and needle and thread grass, *Stipa comata* Trin. & Rupr. The potential problem with this site is not that it is being disturbed but that there is a lack of disturbance. The site has not been grazed or burned for over 20 years and there is a large standing dead component in the aboveground biomass pool. The standing dead biomass contains nutrients that are unavailable for plant growth and reproduction and that would normally be recycled through the soil by grazing or fire. Our objectives for this site were to use fire as a nutrient cycling process to stimulate new growth and reproduction.

The Bernalillo Watershed (BW) site is located south of Placitas, NM and is dominated by a mixture of blue grama, *Bouteloua gracilis* (H.B.K.) Lag. ex Steud., and galleta, *Hilaria jamesii* (Torr.) Benth., grasses and broom snakeweed, *Gutierrezia sarothrae* (Pursh) Britt. & Rusby, an invasive native shrub. This site was an overgrazed juniper woodland prior to the 1950s when the juniper was removed with heavy equipment and the soils were contoured to hold the runoff. Although there has been no significant livestock grazing on this site for 50 years, the native grasses have not recovered, the shrub component is high, and there is evidence of runoff and soil erosion. This site was classified as at risk because of its degraded state and we believe that it is still possible to restore a grassland using ecological processes with limited

outside input. Our objectives for this site are to use prescribed fire to increase the herbaceous plant abundance and subsequently stabilize the soils. We plan to use sequential applications of prescribed fire separated by recovery periods. Our hypothesis is that with each fire the shrub component will decline and the herbaceous vegetation will increase. After three to four restoration fires the herbaceous vegetation should have recovered enough to stabilize the soils and fire can then be used once every 10 years or so for ecosystem maintenance.

The Guaje site is located north of Los Alamos, NM, on the Santa Fe National Forest, Espanola Ranger District. This site is a pinyon, *Pinus edulis* Engelm., - oneseed juniper, *Juniperus monosperma* (Engelm.) Sarg., woodland with a degraded blue grama understory. As with the BW site, the primary disturbance (in this case livestock grazing) has been removed for many years but the grassland community has not recovered on its own. The site was classified as unhealthy because there has been significant runoff and soil erosion with headcutting and arroyo formation evident throughout the study site. Significant outside inputs will be necessary to restore the herbaceous understory and stabilize the soils. We have thinned the trees in an attempt to directly reduce competition for water between the trees and herbaceous vegetation. We used the slash as a surface mulch to indirectly increase water availability to the herbaceous vegetation by reducing evaporative soil water loss and by increasing surface roughness, thereby reducing runoff and increasing infiltration. We plan to reintroduce fire once the herbaceous plant community has recovered to a point that there are sufficient fuels to support a surface fire.

Methods

Vegetation on all study sites was sampled using the Community Structure Analysis (CSA) technique of Puse (1981). The AOS and BW sites both have four, 1 hectare control (unburned) and four, 1 hectare burned plots. Within each plot are three 60 meter CSA transects. The Guaje site has no treatment replication. The thinned and control areas are approximately 20 hectares each and each contains five 100 meter CSA transects.

The AOS site has been burned once in February 1996. Because of adequate fuel quantity and distribution, this site burned well and most of the vegetation was consumed. The BW site was first burned in November 1995 and then again in January 1998. Because of the patchy distribution of the fuels and vegetation and less than optimum conditions, neither fire spread well and both fires left behind substantial patches of unburned vegetation. Fire success might have been greater if we had burned in the late spring, however, due to management concerns and the availability of fire crews, we decided to burn in the fall or winter. The Guaje site was thinned in April 1995. All pinyon less than 20 cm (8 inches) diameter and all juniper were cut by chain saw and the slash was redistributed by hand. Some jackpot burning of large slash accumulations was conducted in the fall of 1996 to reduce the fire hazard. Otherwise no burning has been conducted on the site.

The effect of prescribed fire or thinning treatments was tested by comparing post-treatment conditions on the treated plots to any change on the control plots for comparable time

periods. A repeated measures analysis was utilized with treated vs. control included as a treatment factor, post-treatment years as repeated measures, and the pre-treatment sampling period as a covariate. In some instances, the effect of the treatment was not the same for both post-treatment years (i.e., significant interaction between treatment and time). In these instances, significance of the treatment for individual years was assessed by applying a t-test to the change from pre-treatment conditions for each treatment for a particular year. Type I error for these sets of t-tests was maintained by applying a Bonferroni adjustment to significance levels of individual tests (Miller 1981). All analyses were conducted using SPSS 4.0 (SPSS Inc. 1990).

Results

There was a significant decrease in total herbaceous plant cover on the AOS site immediately after the November 1995 fire and all subsequent sampling periods showed no significant treatment effect (fig. 2A). There was no significant treatment effect on total herbaceous cover on the BW site until after the second fire in January 1998 (fig. 2B). All post-treatment sampling periods showed a significant herbaceous plant cover response to tree thinning on the Guaje site (fig. 2C).

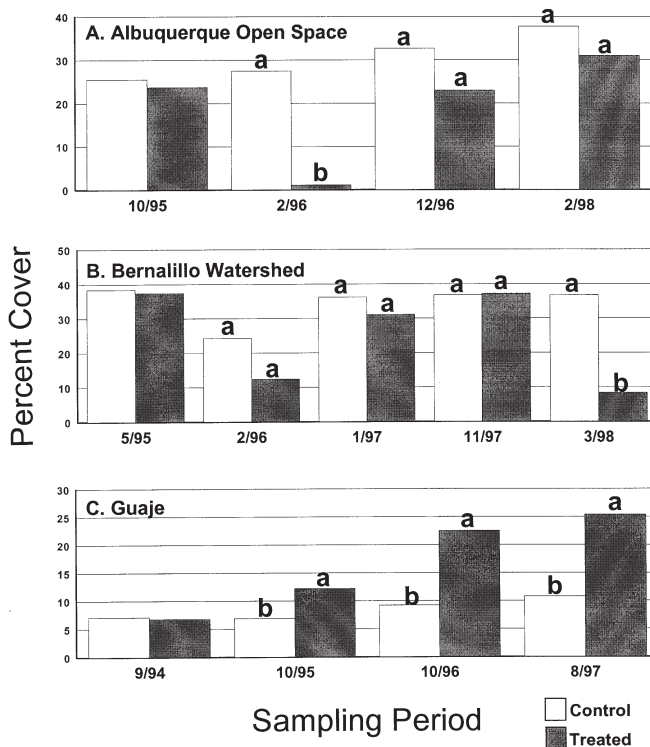


Figure 2—Total herbaceous cover on study sites. Bars with the same letter, within a site and sampling period, are not significantly different ($P > 0.05$). Pretreatment means are displayed for comparison but were used as covariates in the repeated measures analysis and are not included in the multiple t-test evaluation of means.

Discussion

The Rangeland Health Model would predict that natural processes could be used to maintain the functional, compositional, and structural properties of a healthy site, that at-risk sites can be restored using natural processes, and that restoration of unhealthy sites requires outside inputs. Herbaceous plant cover on the healthy AOS site showed a significant response to the first reintroduction of fire. The quantity and homogeneous distribution of herbaceous biomass on the site was sufficient to carry the fire and lead to the desired reduction of herbaceous cover. One growing season following the fire, herbaceous plant cover was not significantly different on the two treatments, indicating a rapid recovery on the burned plots. On this site, fire is easily reintroduced and could be used to increase landscape-scale habitat diversity by creating a mosaic of different successional patches.

The at-risk BW site has not responded as rapidly to prescribed fire treatments. The first fire resulted in a non-significant decline in herbaceous plant cover on the burned plots probably because of the patchy nature of the vegetation/fuels matrix. A substantial portion of the decline in herbaceous plant cover on this site was due to a drought in the winter of 1995/96. Compounding drought stress with fire could have had disastrous results, however, herbaceous cover on both treatments recovered within one growing season which would indicate that this system is very resilient to both drought stress and fire. The second fire, despite the less than optimal burn conditions, resulted in a significant reduction in herbaceous plant cover. We plan to use this 2-3 year cycle of fire and recovery as a test of the restoration potential of the site. However, because this site is not functioning as a healthy grassland, it will take some time for natural processes to affect restoration, if at all.

A good test of the Rangeland Health Model would have been a prescribed burn in untreated pinyon-juniper. Unfortunately, these projects were not originally designed as a test of the Rangeland Health Model, consequently we did not consider using fire as a restoration technique in the unhealthy pinyon-juniper site. Subsequent interpretation of the model indicates that we would have been wasting our time and resources. Although the thinning treatment is more expensive and time consuming the results have been very encouraging. We believe that the herbaceous plant

community has recovered to the point where we can now reintroduce fire. The timing for reintroduction of fire can be critical in this system. A window of opportunity exists between burning too soon and burning too late. Burning too soon can result in hot fires that kill herbaceous plants because the slash has not had time to decompose. Burning too late can result in fires that are not hot enough to kill the cohort of seedling and resprouting trees that are released following the thinning treatment. We believe that the appropriate time to burn this site is in the next 1-3 years. Of course this window will be different for different sites and/or environmental conditions.

Conclusions

Middle Rio Grande upland ecosystems evolved with fire. Restoration and maintenance of their function, composition, and structure will require the use of fire. The potential for successful reintroduction of fire back into upland ecosystems depends upon the status of the system and the disturbances acting on it. The process of objectively identifying and distinguishing between disturbances and problems and determining ecosystem status can lead to insights on appropriate management actions. These objective determinations are best made through the use of data derived from monitoring appropriate abiotic, ecological, and social indicators. Appropriate monitoring procedures and programs would provide data for these pretreatment determinations as well as for evaluation of management treatments and progress toward goals.

References

- Busby, F.E., Ruyle, G.B., and Joyce, L.A. 1995. Minimum ecosystem function: a strategy to integrate methods to classify, inventory, and monitor rangelands. In: N.E. West (ed.) *Rangelands in a Sustainable Biosphere*. Proceedings of the Fifth International Rangeland Congress, Vol. II. Society for Range Management, Denver, CO. 202 p.
- Committee on Rangeland Classification. 1994. *Rangeland Health: New Methods to Classify, Inventory, and Monitor Rangelands*. Board on Agriculture, National Research Council. Washington, DC. 180 p.
- Miller, R.G., Jr. 1981. *Simultaneous Statistical Inference*, 2nd ed. New York: Springer-Verlag. 299 p.
- SPSS Inc. 1990. *SPSS/PC+ 4.0*. Chicago, IL.

Effects of Livestock Grazing on Morphology, Hydrology and Nutrient Retention in Four Riparian/Stream Ecosystems, New Mexico, USA

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Clifford N. Dahm
H. Maurice Valett
Michael C. Marshall

Abstract—Land-use practices such as livestock grazing influence the structure and function of riparian/stream ecosystems. In New Mexico, four streams were selected to determine the impact of moderate livestock grazing on morphology, solute transport, and nutrient retention. Each stream contained a reach currently exposed to grazing and an exclosed, ungrazed reach. Channel width/depth ratios and in-stream standing stock of plant biomass were greater in the grazed reaches. Solute transport was determined by injecting a conservative tracer (NaBr) and applying a one-dimensional transport with inflow and storage (OTIS) model. Grazed reaches exhibited enhanced transient storage, represented by a larger cross-sectional area of storage zone relative to wetted channel area (A_s/A). The extent of nutrient retention was determined by co-injecting a reactive tracer (NaNO_3) with the conservative tracer. Nitrate uptake lengths were shorter in grazed reaches, an indication of more effective nutrient retention. Our results suggest that moderate livestock grazing alters channel structure and vegetation, influencing ecosystem-level processes.

Riparian/stream ecosystems are three-dimensional interfaces that connect terrestrial and aquatic ecosystems. The riparian component extends laterally to the limits of flooding and vertically to the canopy of streamside vegetation; the aquatic system includes stream surface water and shallow groundwater (Gregory and others 1991, Malanson 1995). Riparian vegetation provides numerous ecosystem functions, including habitat, nutritional resources, and bank stabilization (Crawford and others 1993). Riparian vegetation also has a role as a dispersal site and corridor for biota (Gregory and others 1991). As a whole, riparian/stream ecosystems are valuable resources that contribute to water quality and supply terrestrial and aquatic wildlife habitat and recreational uses.

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Anthropogenic disturbances have greatly altered the structure and functioning of these ecosystems, affecting native communities and influencing biodiversity and successional processes. A disturbance is an episode that disrupts an ecosystem, altering resources, substrate availability, or the physical environment (White 1979). While disturbances can promote diversity, it may be at the expense of existing native communities (Hobbs and Huenneke 1992). Alternatively, many ecosystems rely on disturbances to maintain indigenous communities. Disturbances can thus be viewed as potentially destructive or beneficial. Human-induced disturbances often impart protracted adverse effects to natural ecosystems, such as eutrophication. Processes such as productivity and nutrient cycling respond directly to human modification (Vitousek 1994). For example, Likens and Bormann (1995) found that clearcutting a forest was followed by increased nitrate leaching in its catchment. The loss of nitrogen from the upland system and subsequent loading to the stream could be viewed as a destructive ecological disturbance.

In western North America, riparian/stream ecosystems have been subjected to various anthropogenic disturbances such as livestock grazing, agriculture, mining, industrial and urban intrusion, and river regulation (Crawford and others 1993, Malanson 1995). Livestock grazing is the most extensive land management practice in this region (Fleischner 1994). Previous research has addressed the impacts of grazing on particular components of riparian/stream ecosystems, including vegetation, erosion, geomorphology, water quality, and fish habitat (Moyer 1998 and references therein). However, effects of grazing are less understood from the perspective of the ecosystem as a whole, where nutrients can be regarded as an organizing focus (Krebs 1994). Nutrients regulate rates of important ecological processes, including primary productivity and decomposition (Meyer and others 1988). Stream productivity is dependent on both allochthonous inputs of nutrients and nutrient cycling within the ecosystem (Mulholland and others 1995).

In lotic systems, dissolved nutrients are not cycled in place, but are transported downstream with other solutes. The uptake and release of nutrients by biota in streams is described as nutrient spiraling (Newbold and others 1981). Thus, stream nutrients undergo both hydrologic export and

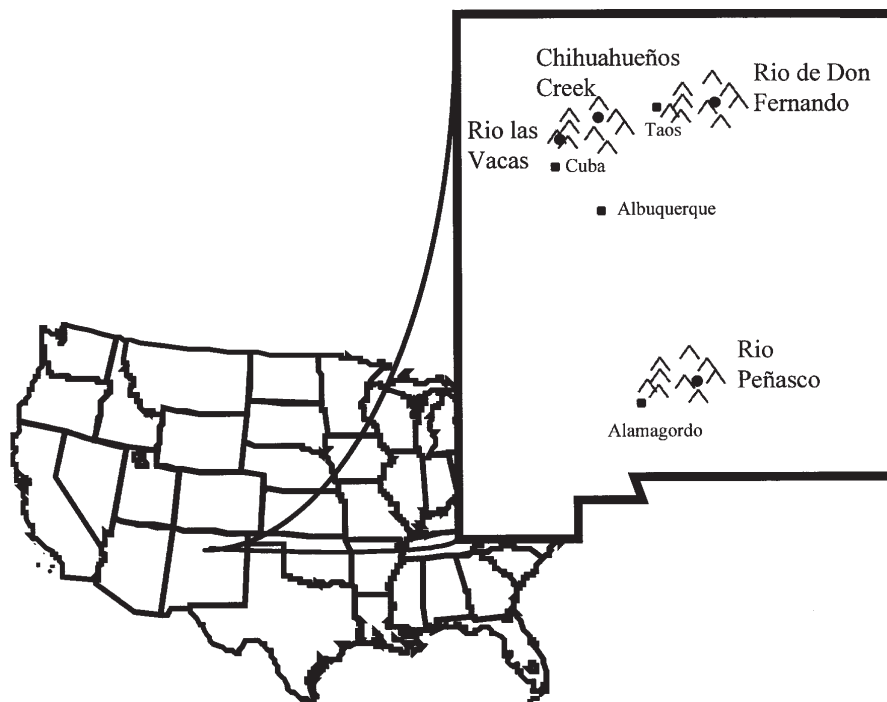


Figure 1—Study site locations, New Mexico, USA.

biological retention (Valett and others 1996). Solutes are also retained hydrologically in flowpaths moving at slower velocities than those predicted by advective transport in the thalweg of a stream (Morrice and others 1997). Hydrologic retention can be determined by the injection of a conservative tracer into the stream. Injection data are incorporated into a transport model that calculates hydrologic parameters such as advection, dispersion, and transient storage (Bencala 1984, Stream Solute Workshop 1990, Runkel and Broshears 1991). Nutrient retention in streams has been measured as nutrient uptake length, the average downstream distance a dissolved nutrient molecule travels before it is utilized by biota (Elwood and others 1983). Nutrient uptake length is inversely related to uptake rate. In a given system, shorter uptake lengths indicate more efficient nutrient cycling.

To maintain ecological functioning and thus support multiple-use status in riparian/stream ecosystems, it is essential to comprehend the movement and retention of solutes, particularly nutrients (Newbold and others 1981, Stream Solutes Workshop 1990). Our research studies the effects of livestock grazing on riparian/stream ecosystem structure and function by examining solute dynamics. In particular, we investigate the influence of moderate livestock grazing on channel morphology, solute transport, and nutrient retention.

Study Sites

Four streams in the Rio Grande catchment of New Mexico were used as research sites (fig.1, table 1). The Rio Peñasco (RP) is located in the Lincoln National Forest in the Sacramento Mountains of southern New Mexico. Chihuahueros

Creek (CC) and the Rio las Vacas (RLV) are situated in the Santa Fe National Forest in the Jemez Mountains of northern New Mexico. The Rio de Don Fernando (RDF) is located in the Carson National Forest in the Sangre de Cristo Mountains of northern New Mexico. Study sites are described in more detail (catchment size, elevation, lithology, stream sediments, and riparian and upland vegetation) in Moyer (1998).

Each site is comprised of a riparian/stream section subjected to moderate grazing (grazed) and a nearby section exclosed from grazing (ungrazed) by the U.S. Forest Service. The management history of many grazing sites is unknown, and grazing intensities have been qualitatively defined in several ways (Fleischner 1994). Although our sites are defined as moderately grazed by the USFS, grazing intensities are not well known. At RP, approximately 250 head of cattle are moved through a 111 ha allotment ($\sim 2.3/\text{ha}$) each November, while 40 to 50 cows pass through an 81 ha CC allotment ($\sim 0.5/\text{ha}$) during July to October. At RLV, roughly 40 head of cattle graze on a 60 ha allotment ($\sim 0.7/\text{ha}$) from June to October. At RDF, about 15 cows graze on a 20 ha allotment ($\sim 0.8/\text{ha}$) from July to October (Moyer 1998).

Table 1—Description of the four riparian/stream research sites in New Mexico.

Site	Stream order	Reach length (m)	Base flow discharge (L/s)	Exclosure age (yrs)
Rio Peñasco	1	120	5	6
Chihuahueros Creek	1	200	18	5
Rio las Vacas	3	400	70	12
Rio de Don Fernando	1	120	5	9

Methods

Field work was carried out from June to August 1997. At each site, paired reaches (grazed, ungrazed) were established. Reach lengths were based on stream discharge (table 1, Moyer 1998). Along each reach, five sampling transects were situated at equal intervals, oriented perpendicular to the longitudinal axis of the stream (Moyer and others 1998). Morphologic, hydrologic and nutrient transport features were examined at each site.

Morphology

Wetted width and average depth of the stream were measured at each transect (Rosgen 1994). Values were used to determine the mean width to depth ratio (w/d) for each study reach. We also measured wetted perimeters and calculated ratios of wetted perimeter to wetted width. Stream beds consisted of patch types dominated by bare (unvegetated) sediments, macrophytes, sedges, and filamentous algae (Moyer 1998). The percent of stream area occupied by each patch type was assessed. Total standing stock of aboveground vegetative biomass was calculated using ash-free dry mass concentrations (Benfield 1996) from stream samples and the area of the channel covered by the respective patch types. The percent of riparian area covered by herbaceous and woody vegetation was measured using 1 m² quadrats. Several additional measurements were made, including channel gradient and sinuosity, dominant sediment type, porosity, total suspended sediments, and subsurface biomass. These are described in Moyer (1998).

Hydrology

In lotic ecosystems, the transport and retention of solutes are determined by hydrologic factors, i.e., solutes flow with the water. Retention occurs when water moves into slower moving zones relative to the main body of water, where it can be considered temporarily stored (Bencala and Walters 1983, Webster and Ehrman 1996). Transient storage zones include shallow groundwater and surface water environments such as pools and backwaters (Moyer and others 1998, Webster and Ehrman 1996). When a solute pulse is transported downstream, some of the solute mass passes into transient storage zones, temporarily decreasing the concentration in the active channel (Runkel and Broshears 1991). Hydrologic parameters were investigated by employing a conservative (nonreactive) solute to act as a tracer with which to formulate data and construct a solute response curve. A concentrated solution of sodium bromide (NaBr) was injected upstream at a constant rate, elevating the stream Br⁻ concentration slightly above background levels. At the downstream end of the reach, Br⁻ concentration was monitored using an Orion 290A ion selective electrode. Surface water samples were collected (1) as the pulse arrived (the rising limb of the solute response curve), (2) once it reached and maintained a plateau concentration, and (3) after the injection was terminated and stream Br⁻ concentrations approached background levels (during the falling limb of the curve). Samples were analyzed in the lab for Br⁻ using a Dionex DX-100 Ion Chromatograph. Solute injections are described in more detail in Moyer (1998).

Data from the injections (Br⁻ concentration vs. time) were plotted as a solute response curve and fit to a hydrologic

model of one-dimensional transport with inflow and storage (OTIS; Runkel and Broshears 1991). This model computes values for five hydrologic variables: advective velocity (bulk fluid motion), dispersion (solute spreading), lateral inflow (inputs of unlabeled water), transient storage (temporary storage of solutes in slow-moving compartments), and the storage zone exchange coefficient (rate of exchange between the storage zone and the channel flow) (Runkel and Broshears 1991). Stream discharge, determined by separate injections at the top and bottom of each reach, is entered into the model. Assuming a steady state discharge for the entire reach, a best-fit line through the Br⁻ response curve is iteratively adjusted by manipulating the following parameters: stream cross-sectional area (A , m²), dispersion coefficient (m²/s), storage zone cross-sectional area (A_s , m²), and the storage zone exchange coefficient (s⁻¹) (Bencala and Walters 1983, Stream Solute Workshop 1990, Moyer 1998). Several hydrologic characteristics were derived based on these parameters, including the area of the storage zone relative to the cross-sectional area of the stream channel (A_s/A , for example Bencala and others 1993). We also determined the hydraulic retention factor (R_h), which describes the amount of time a parcel of water spends in the storage zone per meter of stream ($R_h = A_s/\text{stream discharge}$, Morrice and others 1997).

Nutrient Retention

Nutrient retention was measured by the nutrient uptake length. A reactive tracer, nitrate (as NaNO₃), was co-injected with the NaBr solution. A reactive solute reacts biotically and/or abiotically in the ecosystem, whereby its concentration is subject to change as it is transported downstream (Stream Solute Workshop 1990, Webster and Ehrman 1996). Once the injected Br⁻ reached plateau concentration, samples were collected at each transect and analyzed for NO₃-N concentrations via colorimetric methods (Wood and others 1967) on a Technicon AutoAnalyzer II. NO₃-N values were corrected for dilution and background concentration, natural log transformed, and regressed against distance downstream. Nutrient uptake length was calculated as the negative inverse of the relationship between these two parameters (Newbold and others 1981, Webster and Ehrman 1996, Moyer 1998). Nitrate retention methods are discussed in greater detail in Moyer (1998).

In addition to the injections, surface waters were sampled for background levels of biogeochemically active solutes, including NO₃-N, ammonium (NH₄-N), and soluble reactive phosphorus. These data, along with N:P ratios, are presented in Moyer (1998) and Moyer and others (1998).

Statistical Analyses

Statistical analyses were performed to uncover significant differences for a given variable between grazed and ungrazed reaches, both within and across study sites. Non-parametric t-tests were used to identify differences between each reach for each variable. Pearson Correlation Analyses were used to reveal relationships between the different variables. Step-wise multiple linear regressions were used to create predictive models for key morphological, hydrological, and nutrient retention parameters. Additional information pertaining to the statistical analysis of this research is presented in Moyer (1998).

Results

Morphology

Mean w/d ratios were lower in ungrazed reaches at all 4 sites, with significant differences at CC and RLV ($P = 0.012$ and 0.022 , respectively, fig. 2). Wetted perimeter to wetted width (wp/ww) ratios were 1.5, 1.8, and 1.1 times lower in grazed reaches at RP, CC and RLV, respectively. At RDF, the wp/ww ratio was greater in the grazed reach. Aboveground organic matter was greater in the grazed reaches at RP, RLV, and RDF (fig. 3). Significant differences occurred between grazed and ungrazed reaches at RP and RLV ($n = 3$, $P = 0.0018$ and $n = 3$, $P = 0.039$, respectively). A step-wise multiple linear regression indicated that within each reach, aboveground organic matter was best predicted by w/d ratio ($R^2 = 0.95$, $P = 0.0001$). Riparian vegetation was generally more extensive along ungrazed reaches. Ungrazed reaches contained greater areas of either herbaceous or woody riparian vegetation at all sites (table 2).

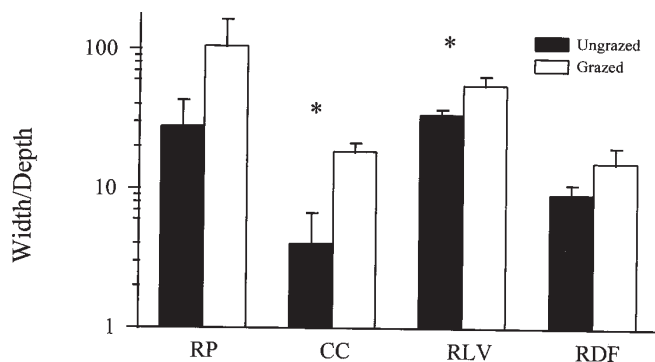


Figure 2—Comparison of wetted width to wetted depth ratios for ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueros Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF). Error bars are standard errors of the mean. Asterisk denotes significance at $p < 0.05$.

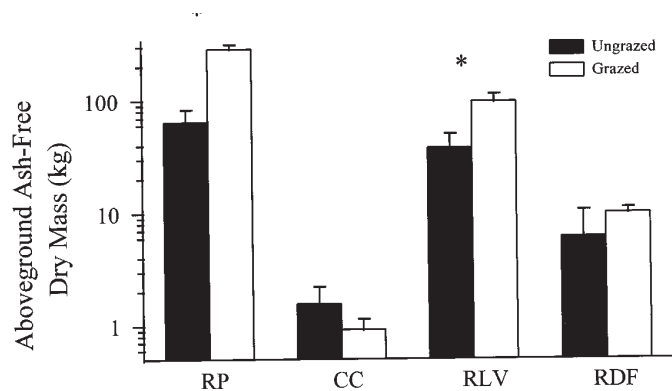


Figure 3—Comparison of total aboveground ash-free dry mass (plotted on logarithmic scale) within ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueros Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF). Error bars are standard errors of the mean. Asterisk denotes significance at $p < 0.05$.

Table 2—Percent cover by riparian patch-types from grazed (G) and ungrazed (U) reaches at the four research sites. Data are means $\pm$ standard errors.

Site	Percent bare soil	Percent herbaceous cover	Percent woody cover
Rio Peñasco-G	28.8 $\pm$ 5.5	71.2 $\pm$ 5.5	0.0
Rio Peñasco-U	5.9 $\pm$ 4.0	94.1 $\pm$ 4.0	0.0
Chihuahueros Creek-G	49.2 $\pm$ 6.6	50.8 $\pm$ 6.5	0.0
Chihuahueros Creek-U	13.4 $\pm$ 4.3	86.6 $\pm$ 4.3	0.0
Rio las Vacas-G	46.8 $\pm$ 11.2	53.2 $\pm$ 11.2	0.0
Rio las Vacas-U	49.1 $\pm$ 8.3	47.1 $\pm$ 9.8	2.5 $\pm$ 1.5
Rio de Don Fernando-G	27.5 $\pm$ 9.1	70.6 $\pm$ 9.3	1.9 $\pm$ 1.9
Rio de Don Fernando-U	43.9 $\pm$ 9.7	49.4 $\pm$ 10.0	6.7 $\pm$ 2.3

Hydrology

The average area of the storage zone relative to the cross-sectional area of the channel (A_s/A) was 45 percent smaller in ungrazed reaches across all sites (fig. 4). A step-wise multiple linear regression indicated that within each reach, total aboveground organic matter was an important predictor of transient storage (as A_s/A , $R^2 = 0.94$, $P = 0.0001$). Hydrologic retention varied between grazed and ungrazed reaches. Hydraulic retention factors (R_h , s/m) were 5.6, 1.3, and 1.4 times greater in grazed reaches at RP, CC, and RLV, respectively. At RDF, R_h in the ungrazed reach was twice the value found in the grazed reach. Based on cross-site comparisons of R_h , grazed reaches demonstrated on average 303 percent more hydraulic retention than ungrazed reaches.

Nutrient Retention

Grazed reaches generally exhibited more efficient nutrient retention compared to ungrazed reaches. Nitrate uptake lengths were shorter in all 4 grazed sites, with significant differences at RP and RDF ($P = 0.0001$ and 0.0068 , respectively, fig. 5, Moyer 1998). A step-wise multiple linear regression indicated that the area of stream channel devoid

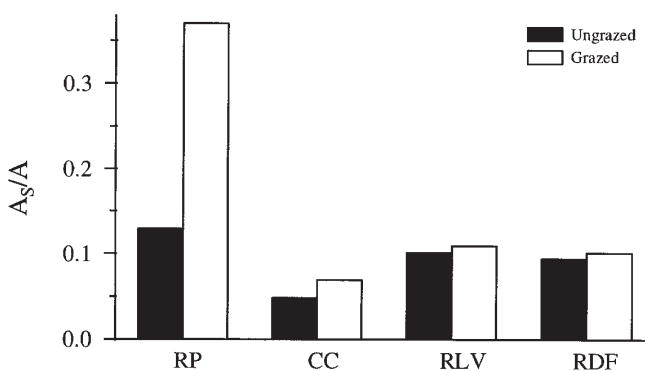


Figure 4—Comparison of area of the storage zone normalized to stream area (A_s/A) for ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueros Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF).

of aboveground vegetation (bare patch-type) was the single most important variable for predicting $\text{NO}_3\text{-N}$ uptake length ($R^2 = 0.97$, $P = 0.0001$, fig. 6). Complete, extensive morphological, hydrological and nutrient transport experimental data and analyses resulting from this research are presented in Moyer (1998) and Moyer and others (1998).

Discussion

Grazed stream channels exhibited mean w/d ratios 150 to 500 percent greater than those in ungrazed reaches (fig. 2). Wider, shallower channels are typical of streams exposed to livestock grazing (Duff 1979, Fleischner 1994). Ratios of wetted perimeter to wetted width indicate less channel complexity in grazed reaches, likely diminishing aquatic habitat variability. Herbaceous and woody riparian vegetation covered a less extensive area along grazed reaches. However, in-stream vegetation (sedges, filamentous algae) was more abundant in grazed compared to ungrazed channels, which were characterized by extensive bare patch-types (Moyer 1998). Channel width exerts a positive influence on the amount of in-stream organic matter. Trampling and loss of riparian vegetation increase w/d ratios and create less stable stream banks (Moyer and others 1998). As a result, in-stream vegetation becomes more abundant, composed mostly of vascular hydrophytes (for example sedges, Moyer 1998). Plants of this type are known to colonize disturbed streams, and are typically succeeded by riparian vegetation such as willows and cottonwoods, which help fortify channel structure (Hendrickson and Minkley 1984, Moyer 1998). Our grazed study reaches appear to be maintained in a state of early secondary succession (Moyer 1998) due to the seasonal disturbance imposed by grazing.

Stream hydrologic retention was also influenced by grazing. Conservative tracer injections demonstrated a greater capacity for transient storage in grazed reaches (fig. 4). Transient storage (as A_s/A) was best predicted by the amount of in-stream vegetation. Mulholland and others (1994) also report a positive relationship between A_s/A and in-stream organic matter (as periphyton biomass). Wetted channel width was also an important influence on solute retention

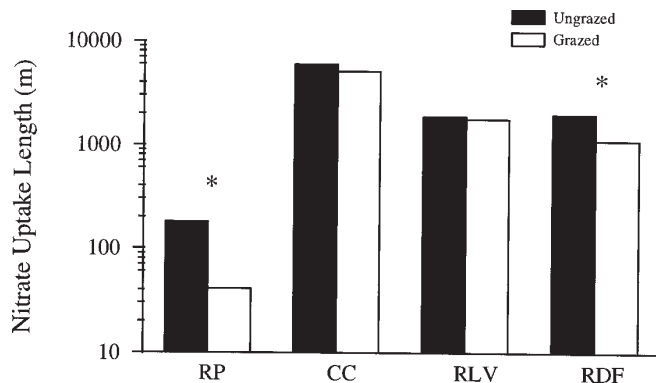


Figure 5—Comparison of nitrate uptake length for ungrazed and grazed reaches of Rio Peñasco (RP), Chihuahueño Creek (CC), Rio las Vacas (RLV), and Rio de Don Fernando (RDF). Asterisk denotes significance at $p < 0.05$.

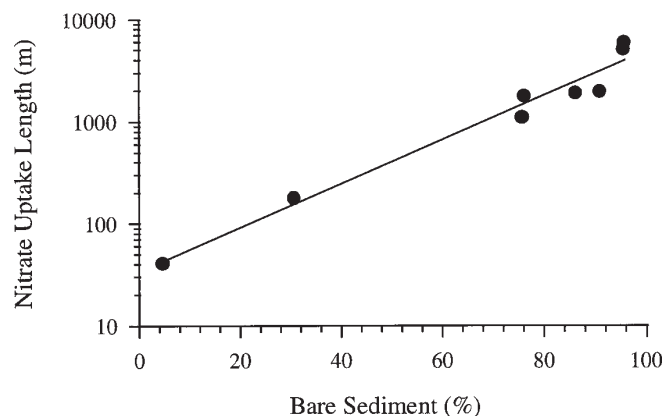


Figure 6—Relationship between nitrate uptake length (plotted on a logarithmic scale) and percent bare sediment. Data are from ungrazed ($n = 4$) and grazed ($n = 4$) reaches.

(data presented in Moyer 1998). These findings suggest that channel structure and in-stream vegetation exert strong, retentive influences on the movement of water through the ecosystem.

Nutrients are taken up more rapidly by the biotic community in grazed reaches, indicated by shorter uptake lengths (fig. 5). Uptake lengths are well correlated with the area of stream bed represented by bare patch types (fig. 6). The results suggest that nutrient uptake length is influenced by the amount of in-stream vegetation. Taken together, in-stream vegetation and the hydraulic retention factor (R_h) account for 99 percent of the variability associated with nutrient uptake (Moyer 1998). Hydrologically, it appears the two factors combine to slow the movement of water, allowing the stream community a greater opportunity to utilize the passing nutrients (Moyer and others 1998). Uptake length is inversely related to stream width, and should decrease as a channel widens (Stream Solute Workshop 1990). A significant, positive correlation exists between aboveground organic matter and w/d. The higher w/d values in grazed reaches may contribute to enhanced nutrient retention by promoting the growth of in-stream vegetation and by the increased sediment area with which solutes can come in contact. The successional state of in-stream biota also affects the potential for solute uptake (Grimm 1987). Nutrients were retained more efficiently in the early secondary successional stage typical of grazed reaches. Efficient nutrient retention also is typical during rapid regrowth of disturbed forest ecosystems (Vitousek and Reiners 1975). As succession proceeds, retention efficiency generally declines (Vitousek and Reiners 1975).

Long-term monitoring of riparian/stream ecosystems following the attenuation or elimination of livestock grazing would enable researchers to consider the effects on succession with more accuracy. Studies could occur on a seasonal basis to include active and dormant grazing intervals, as well as the effect of higher stream discharges (for example during spring runoff). Additionally, a more quantitative, precise definition of grazing intensity would be useful. The effects of moderate grazing versus overgrazing could be compared, enabling researchers to provide land managers with more accurate information (for example the expected effects of a particular grazing regime on a riparian/stream ecosystem).

Conclusions

With respect to ungrazed riparian/stream ecosystems, stream channels are wider and less complex in moderately grazed systems. In addition, in-stream vegetation is more abundant in grazed streams. As a result, nutrients are retained to a greater degree compared to ungrazed sites characterized by less in-stream vegetation and more established riparian vegetation. The effects of grazing on ecosystem-level processes in streams have not been well studied. At the present time we know of no analogous study with which to compare our research. It is uncertain how alterations to hydrology and nutrient retention affect the ecosystem within and downstream of grazed areas. A knowledge of nutrient cycling is an important component in the management of ecosystems, particularly in lands mandated for multiple-use. Land-use decisions such as livestock grazing have the potential to modify nutrient dynamics. The impacts of these changes in nutrient dynamics on riparian/stream ecosystems remain to be determined.

Acknowledgments

Research was funded by Cooperative Agreements 28-JV7-950 and 28-C4-833 to H.M. Valett and C.N. Dahm by the USDA Forest Service Rocky Mountain Research Station and the University of New Mexico. The authors thank Livia Crowley (Lincoln National Forest), Ben Kuykendall (Carson National Forest), Robert Martinez (Santa Fe National Forest), and Richard Montoya (Santa Fe National Forest) for assistance in identifying and accessing research sites. Special thanks to Chelsea Crenshaw, Christine Fellows, Lisa Metz-Roberts, Michelle Baker, John Craig, Jacqueline Walters, and Kathy Smith for field and laboratory assistance.

References

- Bencala, K.E. 1984. Interactions of solutes and stream bed sediments 2. A dynamic analysis of coupled hydraulic and chemical processes that determine solute transport. *Water Resources Research*. 20: 1804-1814.
- Bencala, K.E.; Duff, J.H.; Harvey, J.W.; Jackman, A.P.; Triska, F.J. 1993. Modelling within the stream-catchment continuum. In: A.J. Jackman, M.B. Beck, and M.J. McAleer, eds. *Modelling change in environment systems*. John Wiley and Sons, New York.
- Bencala, K.E.; Walters, R.A. 1983. Simulation of solute transport in a mountain pool-and-riffle stream: a transient storage model. *Water Resources Research*. 19: 718-724.
- Benfield, E.F. 1996. Leaf breakdown in stream ecosystems. In: F.R. Hauer and G.A. Lamberti, eds. *Methods in stream ecology*. Academic Press, San Diego. 579-589 pp.
- Crawford, C.S.; Cully, A.C.; Leutheuser, R.; Sifuentes, M.S.; White, L.H.; Wilber, J.P. 1993. Middle Rio Grande ecosystem: bosque biological management plan. U.S. Fish and Wildlife Service, District 2, Albuquerque, NM.
- Duff, D.A. 1979. Riparian habitat recovery on Big Creek, Rich County, Utah. In: O.B. Cope, ed. *Proceedings of the forum-grazing and riparian/stream ecosystems*. Trout Unlimited, Denver, CO. 91-92 pp.
- Elwood, J.W.; Newbold, J.D.; O'Neill, R.V.; Van Winkle, W. 1983. Resource spiraling: an operational paradigm for analyzing lotic ecosystems. In: T.D. Fontaine III and S.M. Bartell, eds. *The dynamics of lotic ecosystems*. Ann Arbor Science, Ann Arbor, MI. 3-27 pp.
- Fleischner, T.L. 1994. Ecological costs of livestock grazing in western North America. *Conservation Biology*. 8: 629-644.
- Gregory, S.V.; Swanson, F.J.; McKee, W.A.; Cummins, K.W. 1991. An ecosystem perspective of riparian zones. *Bioscience*. 41: 540-551.
- Grimm, N.B. 1987. Nitrogen dynamics during succession in a desert stream. *Ecology*. 68: 1157-1170.
- Hendrickson, D.A.; Minckley, W.L. 1984. Ciengas-vanishing climax communities of the American Southwest. *Desert Plants*. 6: 130-175.
- Hobbs, R.J.; Huenneke, L.F. 1992. Disturbance, diversity, and invasion: implications for conservation. *Conservation Biology*. 6: 324-337.
- Krebs, C.K. 1994. *Ecology*. Fourth edition. HarperCollins College Publishers, New York.
- Likens, G.E.; Bormann, F.H. 1995. *Biogeochemistry of a forested ecosystem*. Springer-Verlag, New York.
- Malanson, G.P. 1995. *Riparian landscapes*. Cambridge University Press, New York.
- Meyer, J.L.; McDowell, W.H.; Bott, T.L.; Elwood, J.W.; Ishizaki, C.; Melack, J.M.; Peckarsky, B.L.; Peterson, B.J.; Rublee, P.A. 1988. Elemental dynamics in streams. *Journal of the North American Benthological Society*. 7: 410-432.
- Morrice, J.A.; Valett, H.M.; Dahm, C.N.; Campana, M.E. 1997. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. *Hydrological Processes*. 11: 253-267.
- Moyer, D.L. 1998. Influence of livestock grazing and geologic setting on morphology, hydrology, and nutrient retention in four southwestern riparian-stream ecosystems. Master's thesis, Department of Biology, University of New Mexico, Albuquerque, NM.
- Moyer, D.L.; Dahm, C.N.; Valett, H.M.; Thibault, J.R.; Marshall, M.C. 1998. Effects of livestock grazing on morphology, hydrology, and nutrient retention in four southwestern stream ecosystems. In: D.F. Potts, ed. *Proceedings of AWRA Specialty Conference, Rangeland Management and Water Resources*. American Water Resources Association, Herndon, VA, TPS-98-1. 397-408 pp.
- Mulholland, P.M.; Steinman, A.D.; Marzolf, E.R.; Hart, D.R.; DeAngelis, D.L. 1994. Effect of periphyton biomass on hydraulic characteristics and nutrient cycling in streams. *Oecologia*. 98: 40-47.
- Mulholland, P.M.; Marzolf, E.R.; Hendricks, S.P.; Wilkerson, R.V.; Baybayan, A.K. 1995. Longitudinal patterns of nutrient cycling and periphyton characteristics in streams: a test of upstream-downstream linkage. *Journal of the North American Benthological Society*. 14: 357-370.
- Newbold, J.D.; Elwood, J.W.; O'Neill, R.V.; Van Winkle, W. 1981. Measuring nutrient spiraling in streams. *Canadian Journal of Fisheries and Aquatic Sciences*. 38: 860-863.
- Rosgen, D.L. 1994. A classification of natural rivers. *Catena*. 22: 169-199.
- Runkel, R.L.; Broshears, R.E. 1991. One-dimensional transport with inflow and storage (OTIS): a solute transport model for small streams. *CADWES Technical Report* 91-01.
- Stream Solute Workshop. 1990. Concepts and methods for assessing solute dynamics in stream ecosystems. *Journal of the North American Benthological Society*. 9: 95-119.
- Valett, H.M.; Morrice, J.A.; Dahm, C.N.; Campana, M.E. 1996. Parent lithology, groundwater-surface water exchange and nitrate retention in headwater streams. *Limnology and Oceanography*. 41: 333-345.
- Vitousek, P.M. 1994. Beyond global warming: ecology and global change. *Ecology*. 75: 1861-1876.
- Vitousek, P.M.; Reiners, W.A. 1975. Ecosystem succession and retention: a hypothesis. *Bioscience*. 25: 376-381.
- Webster, J.R.; Ehrman, T.P. 1996. Solute dynamics. In: F.R. Hauer and G.A. Lamberti, eds. *Methods in stream ecology*. Academic Press, San Diego. 145-160 pp.
- White, P.S. 1979. Pattern, process, and natural disturbance in vegetation. *The Botanical Review*. 45: 229-299.
- Wood, E.D.; Armstrong, F.A.; Richards, F.A. 1967. Determination of nitrate in seawater by cadmium-copper reduction to nitrite. *Journal of the Marine Biology Association of the United Kingdom*. 47: 23-31.

Establishing Riparian Vegetation Through Use of a Self-Cleaning Siphon System

Mark D. Ankeny
L. Bradford Sumrall
Kuo-Chin Hsu

Abstract—Storm water or overland flow can be captured and injected into a soil trench or infiltration gallery attached to a siphon and emplaced adjacent to a stream or arroyo bank. This injected soil water can be used by stream side vegetation for wildlife habitat, bank stabilization or other purposes. The siphon system has three hydrologically-distinct flow regimes: (1) infiltrating flow, (2) cycling outflow, and (3) constant outflow. These flow regimes are dependent upon infiltration gallery design, soil hydraulic conductivity, and rainfall intensity. The design is low-cost and is predicted to be self-cleaning and low maintenance.

Soil functions as a plant growth medium, a regulator and partitioner of water flow, and as a buffer of environmental change. A National Research Council report (1993) reviews soil's role in the hydrologic cycle. Rainfall in terrestrial ecosystems falls on the soil surface where it either infiltrates the soil or moves across the soil surface into streams or lakes. The condition of the soil surface determines whether rainfall infiltrates or runs off. If it infiltrates the soil, it may be stored and later taken up by plants, move into ground waters, or move laterally through the earth, appearing later in springs or seeps. This partitioning of rainfall between infiltration and run-off determines whether a storm results in a replenishing rain or a damaging flood. The movement of water through soils to streams, lakes, and ground water is an essential component of recharge and base flow in the hydrological cycle (Stephens, 1995).

Current engineering practices in the Southwest often reduce infiltration and increase runoff by collecting and conveying storm water quickly and efficiently for ultimate discharge to an existing surface water course. The goals of this management strategy are to reduce hazards to the public and minimize property damage. Although this strategy maximizes the objectives in terms of safety and risk reduction, it prevents the beneficial use of storm waters through recharge. Conveyance times are minimized while flow rates are maximized to remove it from highways, streets and public areas. With concern growing over the availability of water supplies for public and industrial use, alternative uses of storm water must be considered, and if practical, implemented. One such strategy is to recharge

vadose zone aquifers through the use of a sub-surface siphon system to increase recharge and storage (Ankeny and Sumrall, 1998).

The operational objective is to maximize long term water recharge in an infiltration gallery while minimizing long term maintenance requirements. The objectives of the analysis for this structure is multi-fold and includes: (1) determination of hydraulic parameters governing system operation, (2) quantification of water velocities within the system needed to entrain sediment carried into the system, and (3) quantification of the recharge potential of the system through various storm events.

Physical Design

The siphon system is schematically illustrated in figure 1. The siphon behaves as a standard siphon and cycles (drains) as the water level exceeds the *critical head* in the siphon. After the drainage cycle, the siphon breaks and the siphon reservoir refills. The siphon reservoir consists of the *drainage pipe*, the large air-filled pores in the *gravel backfill*, and the air-filled pore space in the surrounding soil (fig. 2). As the siphon refills, water infiltrates into and is redistributed by the soil.

The siphon system consists of a perforated pipe buried in a gravel-filled trench (fig. 2). The perforated pipe is bedded at a nominal slope toward the discharge with an ascending limb angled upward at the terminal end. This upward angled non-perforated portion is formed into a radius of approximately 180 degrees forming an inverted P-trap. This radius is directed downward for discharge. The system operates passively by capturing a point source flow such as a storm drain inlet or other concentrated flow source.

When the siphon cycles, water velocity in the drainage pipe increases, silt in the overlying gravel is back flushed, and water in the drainage pipe reaches entrainment velocity for silt and clay deposited during the infiltration phase of the cycle. Thus, a siphon can take a linear input of water, sediment, and potential energy and turn it into a nonlinear system that retains a large fraction of the water and potential energy while discharging the sediment and part of the water.

Water Flow

TOUGH-2, a multiphase, multidimensional flow and transport code (Pruess 1991) was used to model trench infiltration across a range of soil types and hydraulic heads. Output from this model was used as input for a spreadsheet application to model the infiltration gallery/siphon system.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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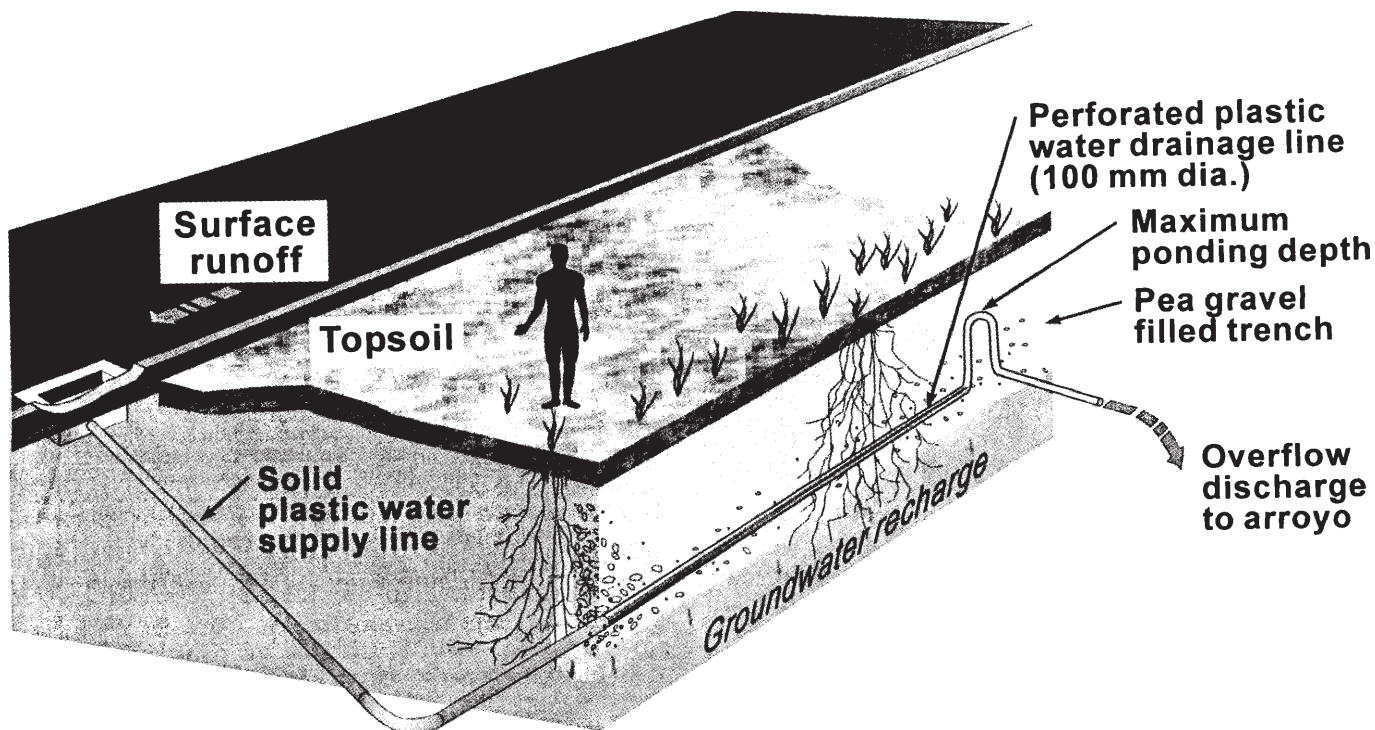
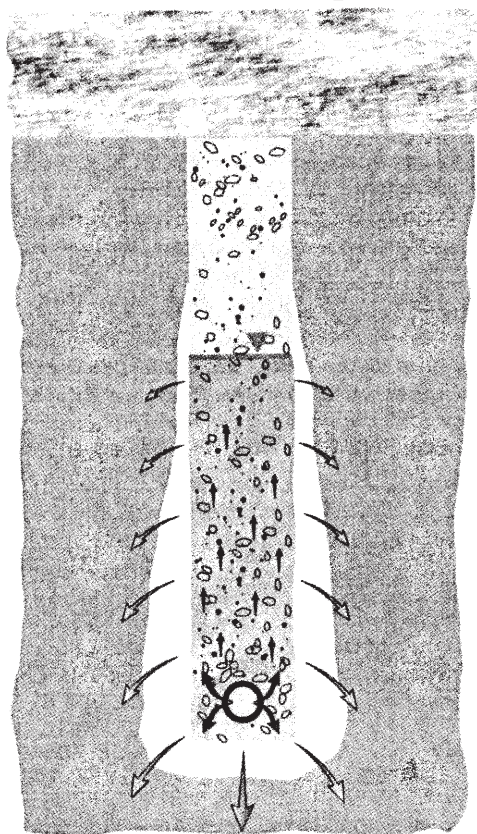


Figure 1—Siphon/infiltration gallery schematic.

Filling



Emptying

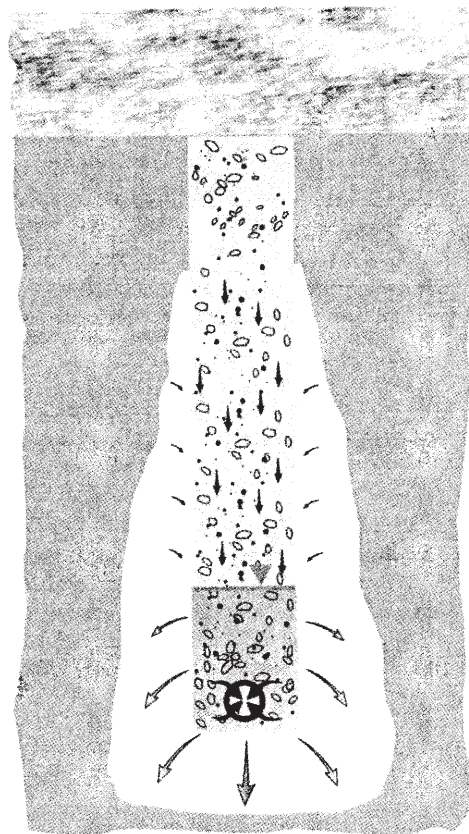


Figure 2—Siphon/infiltration gallery cross section.

The equation governing siphon operation is the energy equation developed by Bernoulli.

$$\frac{P_i}{\gamma} + \frac{V_i^2}{2g} + Z_i = \frac{P_o}{\gamma} + \frac{V_o^2}{2g} + Z_o + h_f$$

where Z = elevation of the pipe (m) subscripts: P is pressure (N/m^2), γ is fluid density (kg/m^3), V is fluid velocity (m/sec), g is the gravitational constant (m/sec^2), and h_f is the head loss within the system (m). Head loss is system dependent and includes friction losses and pipe bends. The subscripts "i" and "o" refer to inlet and outlet values, respectively. This governing equation is used to calculate flow within the spreadsheet model.

In addition to standard hydrologic modeling, the siphon is governed by logical statements embedded within the spreadsheet code to start and stop the siphon based upon water level in the system and upon the previous status of the siphon.

Three flow regimes exist for an infiltrating siphon system: (1) infiltrating inflow, (2) cycling outflow, and (3) continuous outflow, figure 3 shows siphon behavior under the three flow regimes.

The results shown in figure 3 are for a 50 meter long by 0.2 meter wide by 1.75 meter deep soil trench backfilled with

coarse gravel placed over a 0.10 meter diameter perforated pipe. Porosity of the gravel is 35 percent. The siphon empties into an arroyo 1.5 meters below the bottom of the trench. The soil used for calculations is a loamy sand with a permeability of 4.1×10^{-5} m/s. The rational method is used to estimate runoff and a runoff coefficient of 0.90 is used. Rainfall intensity is varied from a drizzle (1 mm/hr) in figure 3a to a light rain (5 mm/hr) in figure 3b and to a downpour (50 mm/hr) in figure 3c. Each rainfall intensity results in a different flow regime.

In infiltrating inflow (fig. 3a), infiltration into the trench bottom and walls exceeds inflow. All water infiltrates, and trench water level is less than the water level needed to activate the siphon (critical head).

In cycling outflow (fig. 3b), when inflow exceeds trench infiltration capacity, the water head in the trench exceeds the critical head, and the siphon is activated. For flow to stop, the rate of outflow must exceed the sum of inflow and infiltration up until the point at which the trench is emptied of water. At this point, air entering the pipe through the inlet or through the perforations is able to break the water column and stop the siphon.

In continuous outflow, an equilibrium is reached between inflow and outflow (fig. 3c). Water level in the trench and infiltration from the trench are constant.

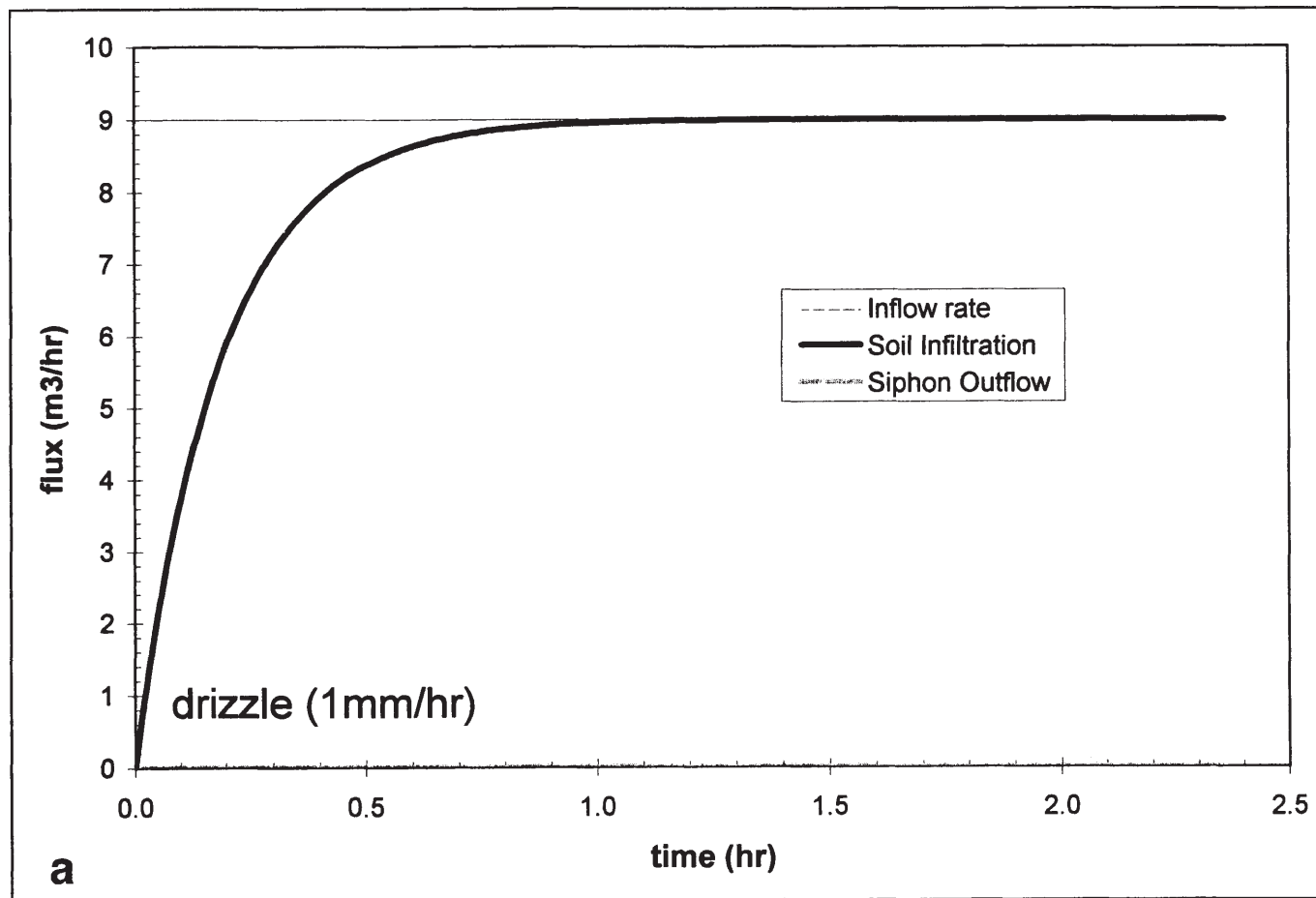


Figure 3—Flow regimes: infiltrating inflow is shown in 3a; cycling outflow is shown in 3b (next page), and continuous outflow is shown in 3c (next page).

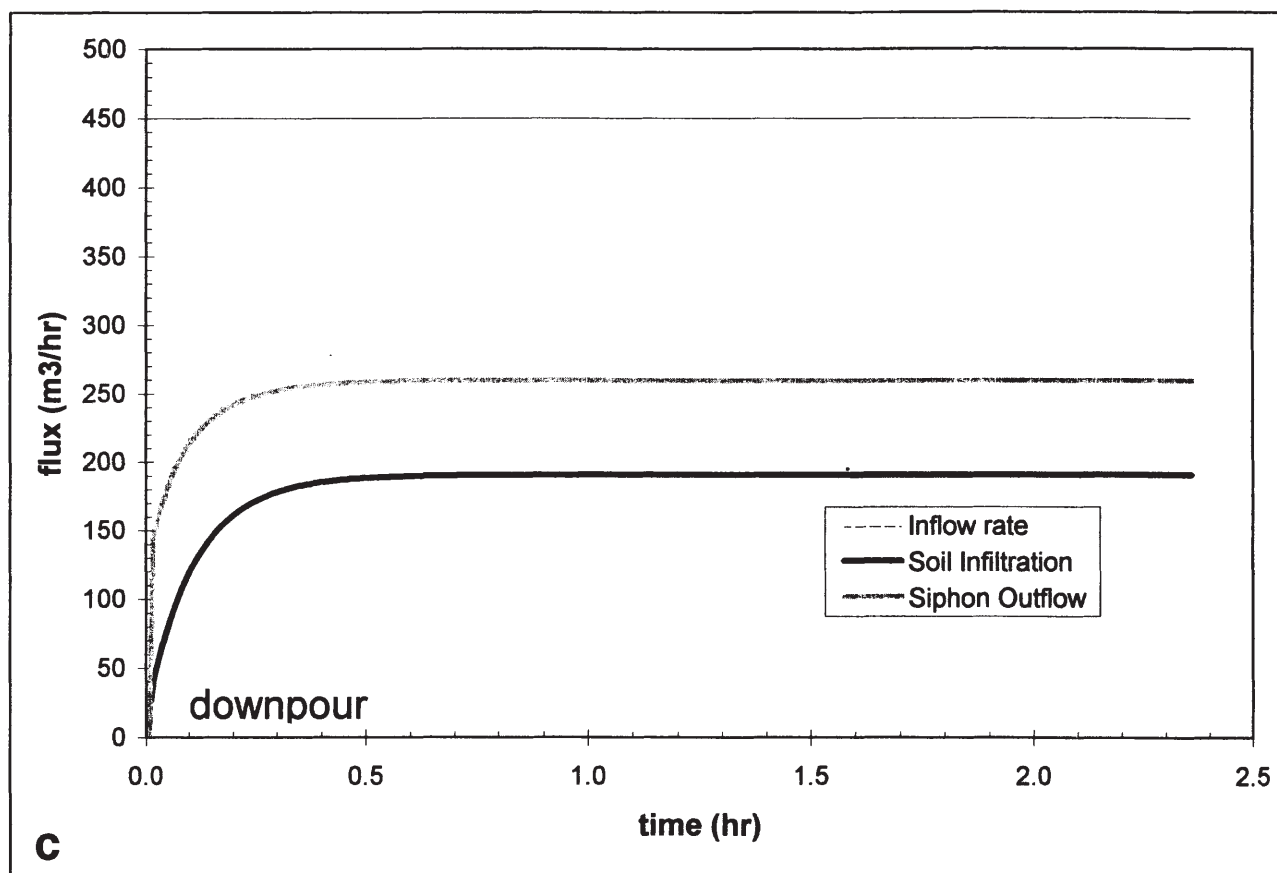
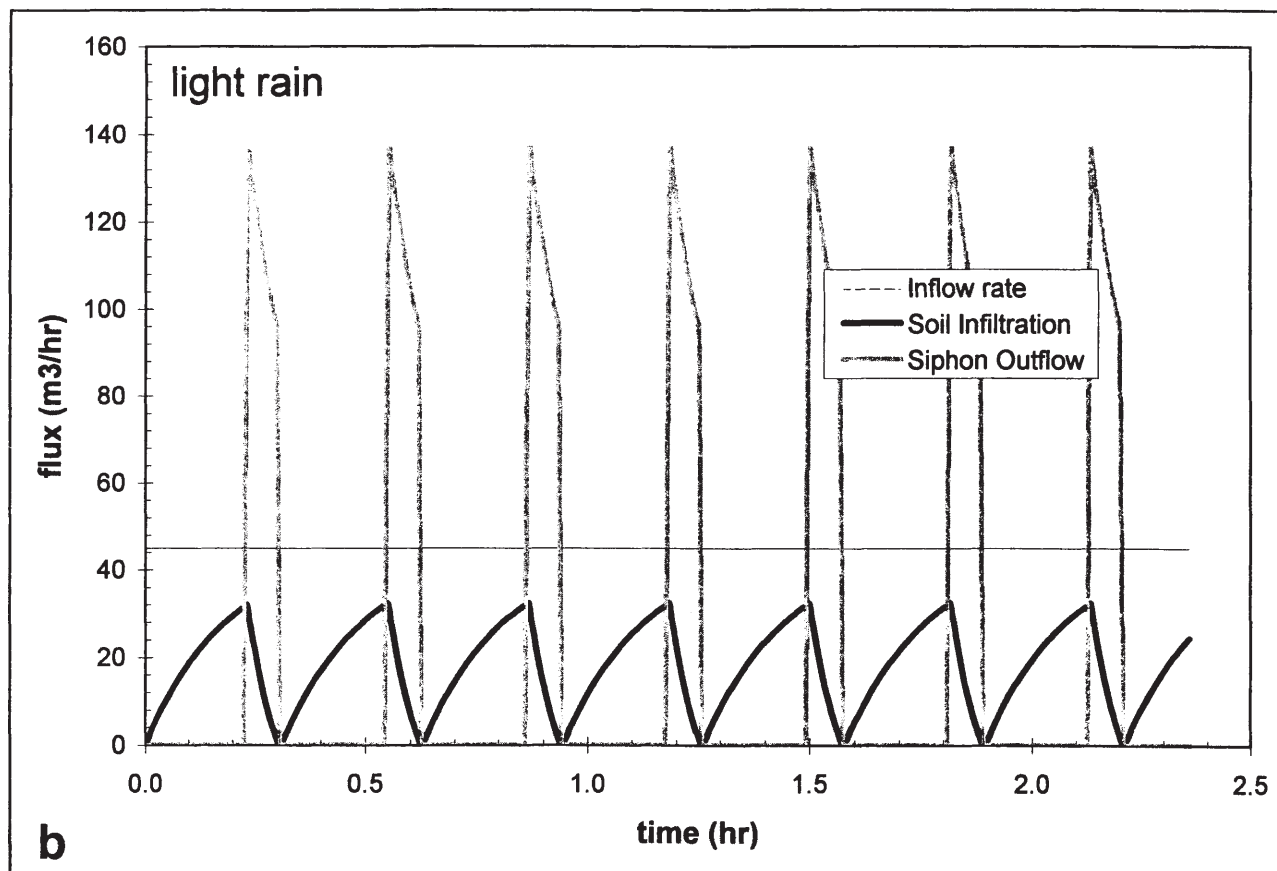


Figure 3— Continued from previous page.

All of these flow regimes potentially can be seen in a single rainfall event. Figure 4 schematically shows rainfall intensity over the course of a typical southwestern thunderstorm. Rainfall starts, quickly builds to maximum intensity, and then slowly tails off. Runoff and erosion intensity follow a similar qualitative pattern. At low rainfall intensities with low sediment inputs, all water infiltrates. As the rainfall intensity increases, sediment input increases, the cycling threshold is reached, and the system starts to cycle. If rainfall intensity increases sufficiently, sediment concentrations may increase, and a continuous outflow flow regime can be established. As rainfall decreases, the system will then revert to cycling outflow, and finally, to infiltrating inflow regimes.

Sediment

Sediment accumulation varies with flow regime. Under infiltrating flow, all water infiltrates and sediment accumulates in the system. However, because infiltrating flow generally occurs during low rainfall intensity events, little sediment enters the system.

During cycling flow, sediment accumulates during the infiltration phase of the cycle and is flushed during the siphon phase. Design parameters must be set to ensure an adequate velocity to entrain sediment in the perforated pipe and to back flush the overlying gravel backfill. The water

velocity obtainable in the system defines the particle size that can be entrained and removed. This velocity sets the upper limit on particle size that can be accommodated by the system.

During constant outflow, little sediment is likely to accumulate in the pipe. However, sustained unidirectional flow into soil is likely to result in some soil plugging and permeability decline. The time frame is likely to be empirically dependent upon soil properties, sediment flux, and particle size distribution.

Vegetation/Siphon System Interactions

Root systems can increase soil saturated hydraulic conductivity over an order of magnitude (Prieksat and others 1994). Increased root biomass results in more root channels as well as an associated increase in faunal activity creating wormholes and other channels. These preferential flow paths increase saturated hydraulic conductivity. In arid and semi-arid systems, plant growth is usually limited by water availability. Because plants maintain fairly constant root:shoot ratios, root mass and soil hydraulic conductivity are often directly correlated with water availability. Thus, a potential positive feedback loop exists where increased water availability from the siphon system increases plant and root mass which increases soil hydraulic conductivity which, in turn, increases water recharge and water availability.

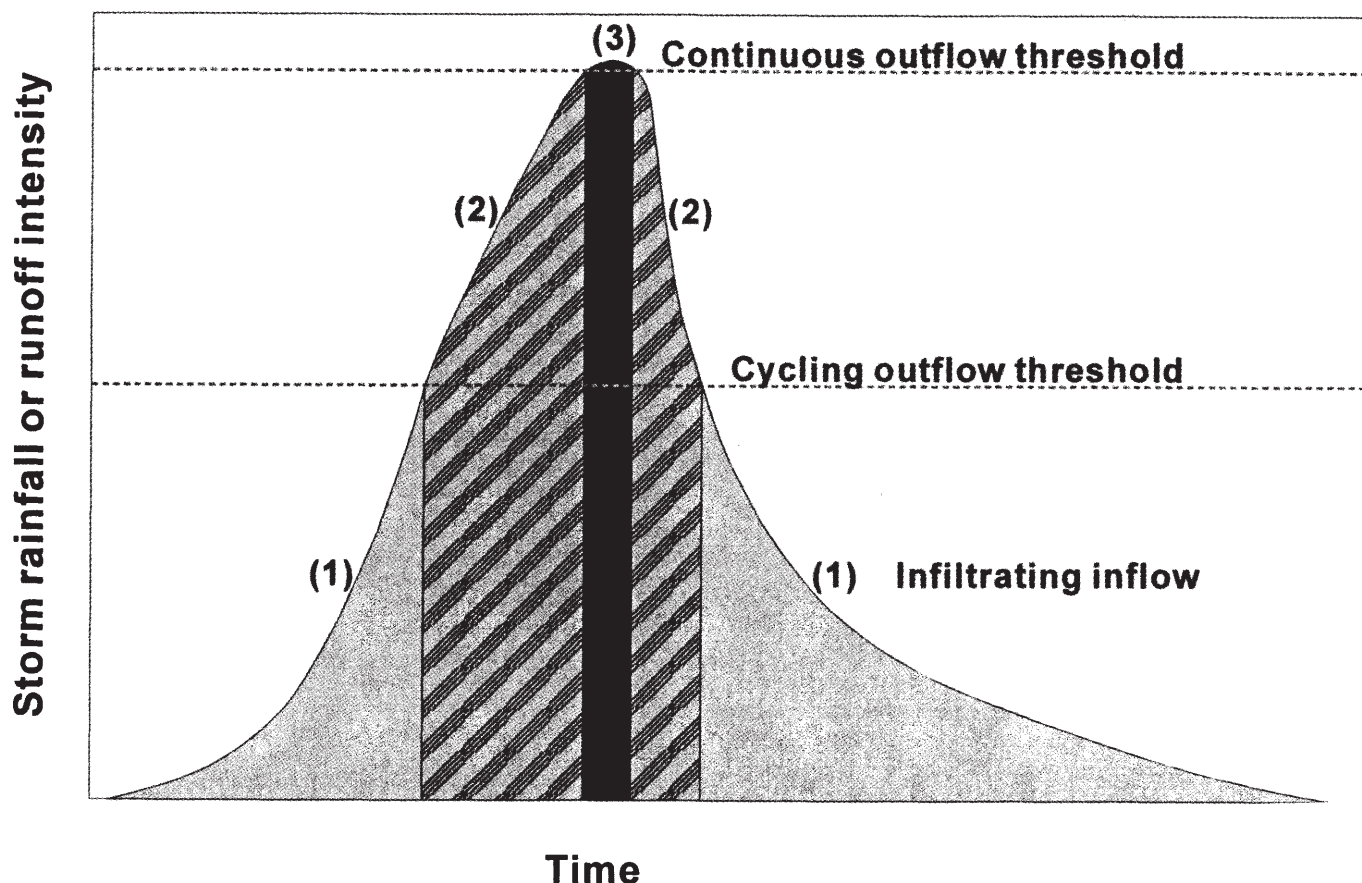


Figure 4—Changes in siphon system behavior over the course of a rainstorm.

These soil-plant-water relationships can be exploited in a siphon system. By increasing water availability, both root growth and hydraulic conductivity of the infiltration system can improve over time. This is particularly true of finer-textured semi-arid and arid soils where little macroporosity exists. Addition of plant roots and water leads to new macropore channels. The reduced carbon released by these roots ultimately results in soil aggregation. These soil aggregation processes are driven by reduced carbon from plants and can be used to combat the natural tendency of pressurized particulate-containing water to plug infiltration systems.

Siphon/Riparian Zone Interactions

Most previous buffer zone and riparian zone research (primarily from the Northeast and the Midwest) has operated on the premise that vegetation is necessary to establish control of run-off. In the western U.S., establishment of vegetation is often problematic due to intermittent water supply. Thus, contrary to what is typically found in the eastern U.S., runoff must be controlled to (re)establish vegetation in arid and semi-arid areas. Runoff control can provide water for establishment of vegetation. One problem is obvious: to obtain the benefits of vegetated buffer zones in arid and semi-arid areas, we need effective methods to convert transient runoff into a steady water source for establishment of vegetation.

Healthy riparian areas provide numerous benefits when viewed as a component of the basic hydrologic unit, i.e., the watershed. Woody riparian species provide channel and bank stability and thus prevent incisement of the channel. Local ground-water levels are maintained due to slow release of bank storage. Natural fluvial processes create channels which efficiently transport water. Water quality is improved where sources of sediment from destabilized banks are eliminated. Shading reduces extreme fluctuations in temperature and evaporative losses from perennial streams. Additionally, riparian zones can attenuate high flood flows while promoting sediment deposition and ground water recharge. These attributes optimize the hydrologic response of a watershed with regards to the storage and discharge of water.

From a soil science perspective, grazing and cropping practices have often reduced soil water storage capacity and increased run-off. A common result has been lowering of local water tables with permanent stream reaches becoming intermittent. From a hydrological perspective (Munzel 1983), these same agricultural practices lead to an exaggerated seasonal flow regime and increase the frequency, severity, and unpredictability of high-volume flows.

Subsurface flow, including that from recharge galleries, generally provides a more constant source of water than surface flow. Obligate phreatophytes, such as cottonwoods, require a constant source of water for survival. Facultative phreatophytes, such as salt cedar (*Tamarix* sp.), tolerate drier periods. In southwestern riparian zone forests (bosques), replacement of native vegetation (such as willow

and cottonwood) by exotics (such as salt cedar and Russian olive) has occurred with watershed degradation over time. The recharge component of the water balance considered critical for maintaining base flow in streams is therefore important in maintaining desired vegetation.

Surface waters have been diverted and infiltrated for thousands of years in various parts of the world (Bruins and others 1986). Wills (1988) summarizes much of the literature on prehistoric southwestern U.S. agriculture and water harvesting. The primary objective of water harvesting is short-term water storage in the soil profile for crop growth. In the southwest, Native American farmers place fields to optimize water and sediment trapping (Nabhan 1984). These relationships among soil, vegetation, and erosion/deposition are eloquently discussed by Jenny (1980). Soils derived from aeolian deposits, alluvium and colluvium are generally considered unsuitable for agriculture because of their high infiltration rates (Tabor, 1995). This characteristic of rapid infiltration, however, appears to improve the suitability of these soils in siphon systems and in arroyo bank stabilization.

While water erosion processes are complex, as evidenced by an abundant and growing amount of technical literature, the principals of erosion control are often stated as these relatively simple principles: Plant, plant residue, or mulch cover should be increased in intensity or in time to decrease energy and volume of run-off water. In the west, local increase of recharge also may facilitate erosion control. The rationale is this: Increased recharge results in increased bank vegetation, and increased bank vegetation reduces bank erosion. Bank erosion is a major contributor to the sediment load in many western streams. Thus, increased recharge from siphon systems is likely to reduce bank erosion on appropriately selected stream banks.

References

- Ankeny, M.D. and L.B. Sumrall. 1998. A siphon/infiltration gallery design for increased recharge. Patent in Progress. U.S. Patent and Trademark Office.
- Bruins, J.J., M. Evenari, and U. Nessler. 1986. Rainwater-harvesting agriculture for food production in arid zones: the challenge of the African famine. *Appl. Geography*. 6:13-32.
- Jenny, H. 1980. *The Soil Resource*. Springer-Verlag, New York.
- Menzel, B.W. 1983. Agricultural management practices and the integrity of instream biological habitat. pp. 305-329, in *Agricultural Management and Water Quality*, F.W. Schaller and G.W. Bailey, eds. Iowa State University Press. Ames, IA.
- National Research Council. 1993. *Soil and Water Quality: An Agenda for Agriculture*. National Academy Press. Washington, D.C.
- Prieksat, M.A., T.C. Kaspar, and M.D. Ankeny. 1994. Positional and temporal changes in ponded infiltration in a corn field. *Soil Sci. Soc. Am. J.* 58:181-184.
- Pruess, 1991. TOUGH-2: A general purpose numerical simulator for multiphase fluid and heat flow. LBL-29400, Lawrence Berkeley Laboratory, Berkeley, CA.
- Stephens, D.B. 1995. *Vadose Zone Hydrology*. Lewis Publications, Boca Raton, FL. 347 pp.
- Tabor, J.A. 1995. Improving crop yields in the Sahel by means of water-harvesting. *J. of Arid Environments*. 30:83-106.
- Wills, W.H. 1988. Early prehistoric agriculture in the American southwest. 188 pp. School of American Research Press, Santa Fe, NM.

Vegetation Classification on the Middle Rio Grande

Joanne Mount

Abstract—This on-going study will provide data on changes in vegetation in the Middle Rio Grande since 1984.

One of the first activities of the Bosque Initiative was a pilot project initiated in June of 1995 by the Army Corps of Engineers to determine if there had been a change in stand structure and species composition of the Bosque since 1984. It was decided from this project that significant change had occurred to warrant further investigation of the entire Middle Rio Grande.

This project includes vegetation between the levees from Cochiti Dam to Elephant Butte Reservoir and the entire flood plain from the south boundary of Bosque Del Apache National Wildlife Refuge to dry land road. The riparian forest consists of approximately 42,020 acres and is 232 river miles in length.

There are two main objectives. The first is to record change in stand structure and species composition since the 1984 Hink and Ohmart Middle Rio Grande Biological Survey. The Hink and Ohmart Biological Survey was done to identify the major types of riparian habitat and to characterize the vegetation and terrestrial vertebrate communities of each type.

The second objective of the this project is to update information on stand structure and species composition of the riparian vegetation and to produce a map that will be available to cooperating agencies. These include:

Bosque Improvement Group
U.S. Fish and Wildlife Service
Rocky Mountain Research Station
U.S. Forest Service, Region 3
Bureau of Reclamation
Army Corps of Engineers
Isleta Pueblo
Santa Ana Pueblo
Middle Rio Grande Conservation District

Aerial photography was flown May 1995, October 1996 and May 1998 at a scale of 1:400. Stand structure and vegetation composition are evaluated using the same methodology Hink and Ohmart used in the 1984 Middle Rio Grande Biological Survey. Six categories are identified based on height of overstory and understory vegetation volume. Polygons are field verified for accuracy using a standard 50x25 meter rectangular plot with a 25-meter line transect. The species composition is evaluated from a threshold of 25 percent or more.

Vegetation polygons are delineated and transferred to Orthophoto base maps. These base maps are projected in UTM (zone 13), datum:NAD 27, spheroid:Clark 1866, at a scale of 1:400. The base maps are edited using Unix LT4X and are then imported into ARC/INFO. The finished product will be available in an ARC/INFO data base. The river will be represented by three reaches: Albuquerque, Isleta and Socorro.

Results will provide participating river management agencies a valuable diagnostic tool that describes the existing vegetation composition and stand characteristics of the Middle Rio Grande from Cochiti Lake to Elephant Butte Reservoir.

Acknowledgments

The author thanks the U.S. Fish and Wildlife Service, and the Bureau of Land Management, and the Albuquerque Corps of Engineers for funding this project. In particular, I thank Jeff Whitney and Debbie Finch for their support.

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Restoration Efforts in the Rio Grande Valley State Park

Ondrea C. Linderoth

Abstract—Restoration techniques for riparian habitats in the Southwest are being widely studied. Efforts for natural regrowth of native species are a high priority. Techniques for native cottonwood (*Populus fremontii*) regeneration are being investigated in the Rio Grande Valley State Park. Experimentation with flooding of riparian zones using different techniques is beginning to show promising results.

The Rio Grande Valley State Park (RGVSP) is a 5000 acre park in the greater Albuquerque area of New Mexico (fig. 1). The Park is managed by the City of Albuquerque, Open Space Division (OSD) in coordination with the Middle Rio Grande Conservancy District. Other agencies with jurisdiction of the river area include the Bureau of Reclamation and the Army Corp of Engineers. These agencies, as well as others, have collaborated on many projects to restore and enhance the bosque in this stretch of the middle Rio Grande. Different techniques for restoration in the Park are being coordinated and/or implemented by OSD.

Cottonwood Pole Planting

The cottonwood pole planting program which is implemented by the OSD, Operations & Maintenance Section, has been successfully running for the last ten years. This program continues to grow in size and success every year. Monitoring of these poles has shown an approximate 90 percent success rate. Almost 1000 poles are planted in the State Park every year. An estimated 10,000 poles have been installed to date.

Methods for installation include the “use of young trees (2-4 years) found growing in riparian areas which can be transplanted or utilizing young trees grown by nurseries for installation” (Barron, 1995). This young stock is utilized when dormant and placed in pre-drilled holes in the riparian area. The holes must be drilled to the groundwater table. A single pole is placed into the hole and pushed through until it is touching the water. Poles are then protected using woven wire wrapping. This material protects the young tree from potential predators such as beaver.

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Experimental Microirrigation Project

Open Space is working in coordination with the USDA, Natural Resource Conservation Service (NRCS), Plant Material Center on an experimental plot in the RGVSP. NRCS established an experimental microirrigation site on the west side of the river near the Calabacillas Arroyo and has been monitoring the site since 1997. This is a one-acre study site with approximately three fourths of the site being enclosed by a fence. The site is irrigated through a well system utilizing three types of microirrigation. Weed control was performed by hand and “cottonwood seedlings were sprayed monthly from August to October 1997 to control cottonwood leaf beetle” (USDA, NRCS, 1997).

The site has proven to be successful in generating native cottonwood seedlings by keeping the soil moist during seed dispersion. “Over 12,500 seedlings were established at this one-acre site by October 1997” (USDA, NRCS, 1997). Due to this success, an additional site is being created on the east side of the river.

Ground Level Manipulation

A new concept that was implemented during the restoration of a burned site was to include sculpting of the ground level to partially inundate the area with ground water when the river is running high. This area, called the Zoo Burn site, is located on Tingley Drive on the east side of the river behind the Zoo. This treatment allowed the cottonwoods, willows, seepwillows, and other species that were planted at the Zoo Burn site to be closer to the water source and establish more successfully. The area is partially flooded during high water and native wetland species have been planted and established in this ‘moist soil’ area. The site is now in its second season and all species that were planted as well as volunteer native species are thriving. Because of the ‘wetness’ of the site, migratory bird species are also attracted to the area and sandhill cranes have been viewed in the area. Though no statistical or definitive information has been collected at this time, observation of the progress of the sight seems to show that his type of restoration is very successful.

Exotic Species Removal

Removal of exotic species is another management tool that is being implemented in the RGVSP. In coordination with the U.S. Army Corps of Engineers and the USDA Natural Resource Conservation Service, a salt cedar removal project was implemented in 1997 as mitigation for the Middle Rio Grande Flood Protection: Bernalillo to Belen, New Mexico levee rehabilitation project. Within the RGVSP, the project

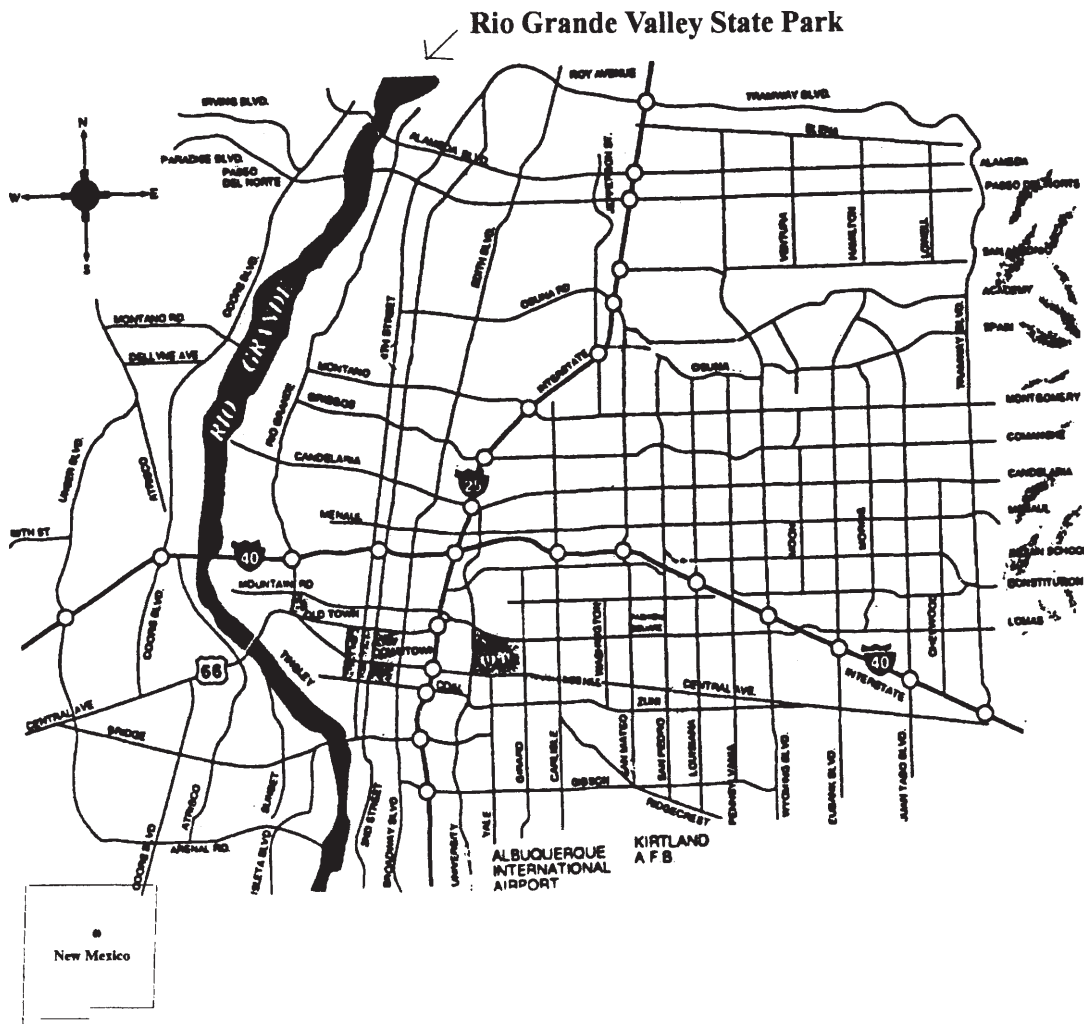


Figure 1—Location map: Rio Grande Valley State Park, Albuquerque, NM.

took place on the west side of the river between Alameda Blvd. and La Orilla channel. Three areas were treated for removal of salt cedar and follow up spraying of Tamarisk (*Tamarix pentandra*) seedlings as mitigation for the rehabilitation project; one at the La Orilla channel outfall, and two on the east side of the river south of Paseo del Norte. These areas have recently been replanted in 1998 with native species.

The plan for this mitigation is spelled out in the *Fish and Wildlife Mitigation Plan* of the Final Environmental Assess non-native species within the project area. The techniques followed for removal are as follows: Sites were chosen where large patches of the exotic species, Tamarisk, existed. The site was then cleared and grubbed “to remove the roots and discourage re-sprouting” (ACOE, 1996). Follow up included herbicide treatment of sprouts and removal of dead and down material prior to replanting. The material that was removed was burned on site. Replanting using cottonwood poles occurred during the dormant season (January-April) following the removal of Tamarisk. The mitigation will

occur over a three year period with 10 sites identified throughout the RGVSP and the Corrales Bosque Preserve just north of and adjacent to the RGVSP.

Created Wetlands

The Alameda Wetland project is currently under construction at the Alameda/Rio Grande Open Space property at the north end of the RGVSP. This property was jointly purchased by the City of Albuquerque, Open Space and Bernalillo County. Construction of a parking lot was completed in 1997 by Bernalillo County. The second phase of activities for the site is the implementation of a created wetland. The project is being constructed by the Bureau of Reclamation, with additional funding from the U.S. Fish and Wildlife Service for the liner, and Intel providing funding for wetland and upland plant species. Open Space is planning and overseeing project implementation while providing additional funding. Open Space will manage and

maintain the wetland once it is completed. This will be a five acre wetland created for increased habitat near the RGVSP riparian zone.

Over the last 60 years, the Middle Rio Grande bosque has lost approximately 85 percent of its wetland areas. This as well as the increased population in the Albuquerque area, has created pressures on habitat and the wildlife that dwell within. Opportunities for projects of this kind will continue to be investigated in the RGVSP to meet Open Space goals to increase wildlife habitat.

Albuquerque Overbank Project _____

Open Space is one of the participants involved in a multi-agency project to manipulate the riverbank to encourage overbank flooding and, in turn, potentially foster natural cottonwood generation. The Albuquerque Overbank Project has been implemented in coordination with the Bureau of Reclamation (lead agency), Middle Rio Grande Conservancy District, University of New Mexico, New Mexico Natural Heritage Program, and Open Space. The site is approximately 3 acres in size and is located on the west side of the river north of Rio Bravo Blvd. The area has been successfully prepared for natural overbank flooding by removing existing non-native vegetation including Russian Olive (*Elaeagnus angustifolia*) and Tamarisk (*Tamarix pentandra*). It was felt that there was a need for action due to the decline of the "ecological health of the bosque as reflected by exotic species' invasions and reduced native stand vigor" (BOR, 1998). From this, the need is to then understand how to reestablish a healthy native riparian habitat. This is one of the few geographical areas in the RGVSP that allowed an opportunity for overbank flooding without threat to private home sites.

The project is currently being monitored for vegetation populations and species diversity, groundwater level and nutrient analysis, soil analysis, and surface water fluctuations. A draft outline has been compiled to date which will

be developed into a final report for distribution. The site is currently receiving minimal flooding and the group is exploring options for release of additional waters.

Discussion _____

All of the projects discussed have had positive effects on riparian restoration in the RGVSP. Techniques for providing moist soil or natural inundation by water in the riparian zone are most successful in fostering native cottonwood generation. Ongoing study of these projects and implementation of follow up or varying studies will help elaborate which techniques or techniques are the most successful in restoring native riparian habitat.

Acknowledgments _____

The author wishes to thank the Middle Rio Grande Conservancy District, Army Corp of Engineers, Bureau of Reclamation, University of New Mexico, New Mexico Natural Heritage Program, Natural Resource Conservation Service, Intel Corp. and the U.S. Fish and Wildlife Service for their participation and support of these project studies.

References _____

- Barron, Tony. 1995. Restoration guidelines for riparian areas using dormant stock "pole" cuttings. City of Albuquerque, Open Space Division, Albuquerque, NM. 4 p.
- United States Army Corp of Engineers, Albuquerque District. 1996. Revised Fish and Wildlife Mitigation Plan for Middle Rio Grande Flood Protection: Bernalillo to Belen, New Mexico, Corrales Unit. 6 p.
- United States Department of the Army, Natural Resources Conservation Service, Los Lunas Plant Materials Center. 1997. Annual Interagency Riparian Report (1997) Eleventh Edition. 31 p.
- United States Department of the Interior, Bureau of Reclamation. 1998. Draft Albuquerque Overbank Project. 2 p.

River Bar Vegetation Mowing Response in the Middle Rio Grande

Esteban Muldavin
Elizabeth Milford
Yvonne Chauvin

Abstract—The Bureau of Reclamation routinely mows vegetation on side bars along the Rio Grande to assist with river flow management. To address the question of how such mowing affects vegetation composition and structure, three bars in the middle Rio Grande near Albuquerque, New Mexico were selected in 1994 for an experimental mowing program. Three 50-foot-wide strips on each bar were left unmowed, with the area between the strips mowed as usual. This mowing pattern was repeated in 1995 and 1996. In August 1996, vegetation composition, abundance and structure were measured under the two conditions of the treated bars and at one additional bar with no history of mowing. Species composition and abundance were compared among sites and treatments using ANOVAs and canonical discriminant analysis. The greatest negative effect was on the native cottonwood where there were significant declines of 70-90 percent on some sites with respect to cover, stems and individuals. Mowing also reduces the exotic Russian olive cover by 50-70 percent on sites where it is dominant. Although cover may decline, Russian olive often responds by resprouting and creating vigorous multiple-stemmed individuals. Coyote willow was affected less by mowing; at the site with the most willow cover (Belen), declines in both cover and the number of individuals were only about 32 percent. This relatively higher mowing tolerance may reflect coyote willow's greater adaptiveness to natural disturbances such as flooding. What is clear however, is that regardless of what shrubs are dominant, cottonwood is always the most negatively affected by mowing.

The Bureau of Reclamation (BOR) conducts mowing of the vegetation on side bars along the Rio Grande to assist with management of the river flow. Questions have arisen about the effect of this mowing on vegetation composition and structure. Are exotic species or natives affected by mowing? Is there an effect on overall biodiversity? How is the structure of shrub vegetation (stem number and size) affected? An experimental mowing and not-mowing program was begun by the BOR in 1994 on three river bars in the middle Rio Grande near Albuquerque, New Mexico. The bars were treated in the winters of 1994, 1995, and 1996. To evaluate the effects of mowing and not-mowing, the New

Mexico Natural Heritage Program (NMNHP) measured vegetation composition, abundance and structure at these sites in the summer of 1996. Permanent monitoring sites were established and the results from the first year's sampling with respect to exotics and overall plant species diversity and stand structure are reported here.

Methods and Materials

Study Sites

In 1994, three river bar sites along the middle reach of the Rio Grande near Albuquerque, New Mexico were selected for experimental mowing and not-mowing of vegetation. These sites had been subjected to ongoing mowing by the BOR for a number of years. They are located from north to south along the Rio Grande at the I-40, I-25 and NM 6 (Belen) bridges, respectively (fig. 1 and 2). On February 21, 1994 each bar was mowed in such a way as to leave three, 50-foot-wide strips unmowed with intervening mowed vegetation. Each strip was marked with either rebar or wooden stakes. The intervening areas were, on a continuing basis, mowed the following winters of 1995 and 1996. The style of mowing was not documented, but there are indications that mowers may have differentially treated cottonwoods by mowing around them in the treatment areas.

As a comparison, a site with no known history of mowing, south of the Central Avenue bridge and parallel to Tingley Beach, was included in the study. This site consists of a side bar and an island bar. Thus, there are three sites with a history of mowing that now contain strips of vegetation that have not been mowed for three years, plus one site that has never been mowed.

The I-40 site is located on the west bank of the river between the Central and I-40 bridges. It is dominated by Russian olive (*Elaeagnus angustifolia*) in the shrub layer, with some younger cottonwoods (*Populus deltoides* var *wizlezenii*) and seepwillow (*Baccharis salicifolia*). The understory is dominated by alkali sacaton (*Sporobolus airoides*) with fair amounts of Baltic rush (*Juncus balticus*) and saltgrass (*Distichlis spicata*) (fig. 3 and 4).

The unmowed side bar and island bar south of Central, hereafter referred to as the Tingley Beach site, is located on the east side of the river approximately a mile south of the Central bridge. The side bar has one major and a few smaller high-flow channels cutting through it. The nearby island bar lies 20 meters to the northwest across a shallow channel. It has a raised central portion, which is dominated by shrubs, with lower areas at the edges and north and south points dominated by grasses and alfalfa (*Medicago sativa*).

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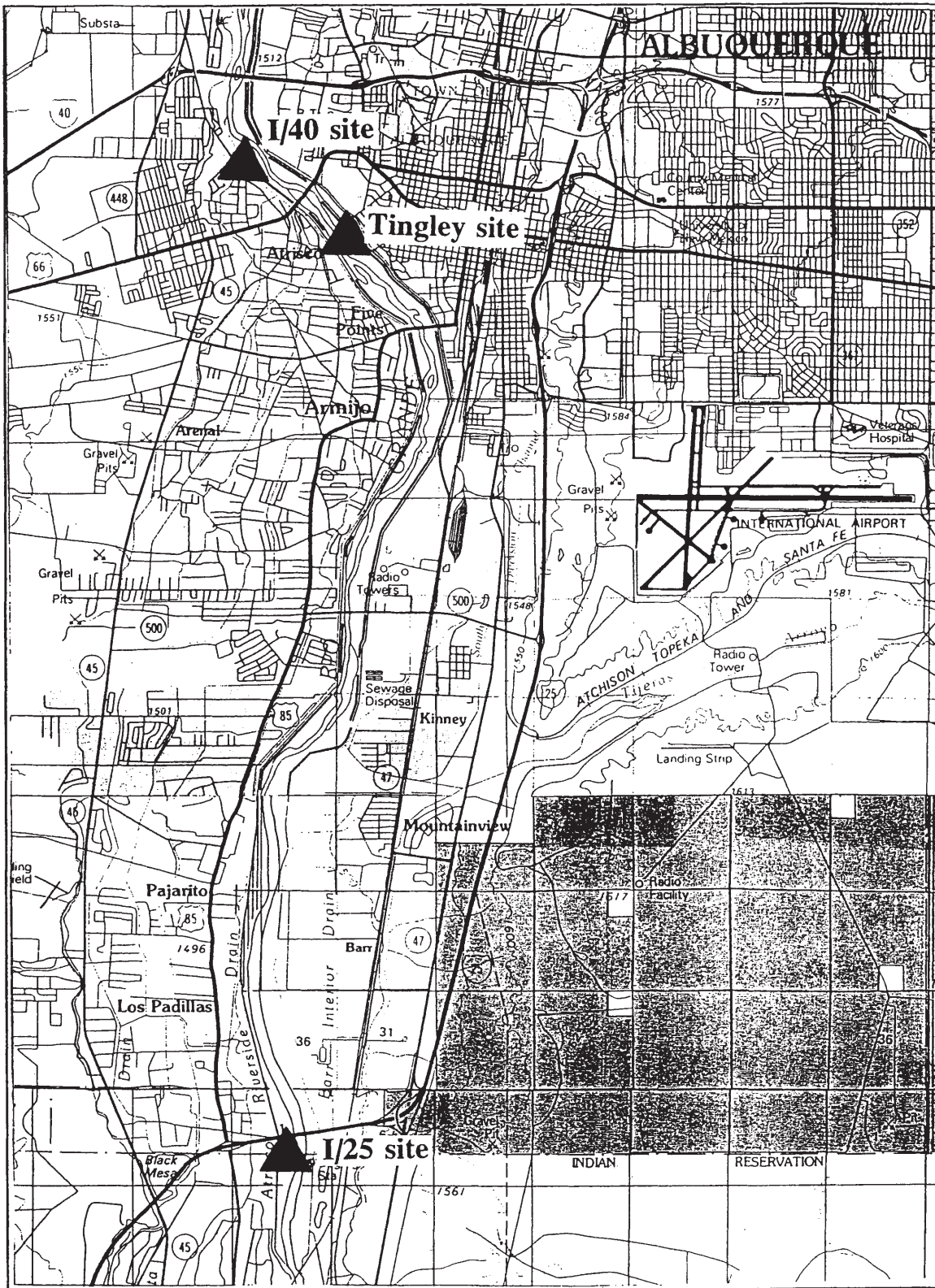


Figure 1—Map showing locations of I-40, Tingley Beach and I-25 study sites.



Figure 2—Map showing location of Belen study site.



Figure 3—Photo of I-40 site, looking down the Line 2 control (unmowed) transect. Many Russian olives and cottonwoods are now over three meters in height after three years.



Figure 4—Photo of I-40 site, looking south across Line 3 from the treatment (mowed) transect to the control (unmowed) transect in the background. Russian olive is abundant and cottonwoods are scattered on this site.



Figure 5—Photo of Tingley side bar site, looking north at line 2. Heavy coyote willow cover is typical of this site with some scattered cottonwood regeneration.

Transects were only established on the higher portion of the island bar, as this is area is more representative of the other bars being examined. Both the bar and the island are dominated by coyote willow (*Salix exigua*) in the shrub layer, with the understory dominated by meadow fescue (*Festuca pratensis*) (fig. 5 and 6).

The I-25 site is located on the west bank of the river immediately south of the I-25 bridge across the Rio Grande, and just north of Isleta Pueblo. In the spring of 1994 this site was burned when the neighboring bosque caught fire. The shrub layer is dominated by Russian olive with a fair amount of coyote willow. The major understory plants are alkali muhly (*Muhlenbergia asperifolia*), heath aster (*Aster ericoides*), vine-mesquite (*Panicum obtusum*) and saltgrass (fig. 7 and 8).

The Belen site at the NM 6 bridge is on the west bank of the river just south of the bridge within Senator Willie M. Chavez State Park. The dominant shrub is coyote willow with more cottonwood and Russian olive than the Tingley site. The understory is dominated by alkali muhly with strong components of Nebraska sedge (*Carex nebrascensis*), seepwillow, and Indianhemp (*Apocynum cannabinum*) (fig. 9 and 10).



Figure 6—Photo of Tingley island bar site, looking northwest at the island from the side bar. The central raised portion of the island is dominated by coyote willow.



Figure 7—Photo of I-25 site, looking down Line 2 treatment (mowed) transect showing heavy Russian olive shrub cover typical of this site.



Figure 9—Photo of Belen site, looking down Line 1 control (unmowed) transect showing heavy coyote willow cover.



Figure 8—Photo of I-25 site, looking south across Line 2 from the treatment (mowed) transect to the control (unmowed) transect in the background. The mix of coyote willow and Russian olive is typical of mowed transects at this site. This area was burned in the spring of 1994.



Figure 10—Photo of Belen site, looking south across Line 1 from the treatment (mowed) to control (unmowed) transect in the background. Heavy coyote willow cover with scattered cottonwoods is typical of this site.

Sampling Methods

To measure vegetation composition and structure, permanent vegetation monitoring transects were established on all four sites. The mowed and unmowed strips were relocated from maps, field marks, and with the aid of BOR personnel. On the three experimentally mowed sites, a transect line was established down the center of each of the three unmowed strips, with three comparison transects established in the mowed adjacent areas, for a total of six transects per site. The mowed transects were always placed to the north of their unmowed mate. Also, three transect lines each were established at the unmowed side bar and island sites. Transect pairs were numbered one to three, working north to south, and labeled C or T for control (unmowed) or treatment (mowed). From this point forward mowed transects are referred to as “treatment” and unmowed transects as “control”.

All transects were permanently marked at each end with a meter length of rebar driven into the ground with about a third of the length showing, then covered with white PVC pipe. Metal identification tags were attached to the start rebar of each transect. The rebar locations were recorded with a Global Positioning System (GPS) unit and differentially corrected to +/- 5 meters (UTM). Photos were taken along the transects from each end along with representative photos taken of each site and are provided in a supplementary folder.

Beginning at a randomly placed start-point on the transect lines, one meter square quadrat frames were placed on the upstream side of the transect lines at regular intervals, ensuring 10 quadrats per transect line for a total of 30 per treatment and 30 for control at each site.

In each quadrat, for each shrub species, the number of stems in 5 cm diameter root crown (DRC) classes were counted and the average height by DRC class estimated. Stem numbers were counted from the root-crown, and individuals were estimated on proximity of emergent stems. Additionally, the aerial cover of all vascular plant species was estimated using a modified Krajina cover scale (table 1).

Sampling was performed August 13-23, 1996, at the end of the peak of the growing season.

Analysis

Data were entered into the NMNHP data system following NMNHP quality control protocols, then analyzed using the SAS statistical package versions 6.11 for aix (SAS 1990). Species identifications were confirmed from the voucher specimens, and the specimens were deposited at the University of New Mexico herbarium.

Species composition and abundance were compared among sites and treatments, particularly with respect to exotic versus native species. Analysis of variance (ANOVA) was used to compare the average cover, number of stems and number of individuals per quadrat for the most common shrub species across site, treatments type and site/treatment type combined. ANOVA was also used to compare the most common understory species across site, treatment type and site/treatment types combined. Pair-wise comparisons were made using Fisher’s Least Significant Difference (LSD) means test (Sokal and Rohlf 1981).

Table 1—Modified Krajina scale used to estimate aerial cover of all vascular plant species.

Symbol	Percentage cover	Scaler
	<i>Percent</i>	
+0	N/A	Outside quadrat
+	N/A	Solitary or very few
1	<0.1	Seldom cover
2	<1	Very scattered
3	1-4	
4	5-10	
5	10-25	
6	25-33	
7	33-50	
8	50-75	
9	>75	
10	100	

Species diversity was assessed with three different indices. Species richness was evaluated from the direct counts of species number per transect, a method considered valid when samples are of equal size (Ludwig and Reynolds, 1988). The modified Hill’s ratio evenness index (E5) was used to assess species evenness. Hill’s N1 diversity index, which estimates the number of abundant species present, was used to assess species diversity (Ludwig and Reynolds, 1988).

To evaluate overall relationship among sites and species, multivariate canonical discriminant analysis was performed on both the shrubs and understory species for site/treatment type combined. Canonical discriminant functions optimize a linear combination of the original variables to maximize discrimination among groups. The correlation between the canonical functions and the original variables can be determined and is reported as an among-group canonical structure. This structure can then be used in a way similar to correlation coefficients to evaluate the importance of each original variable in discriminating among groups.

Results

There were 67 species encountered in the study. The top three shrubs (Russian olive, Rio Grande cottonwood and coyote willow) and the top seven grasses and forbs were selected for univariate Analysis of Variance (ANOVA) and multivariate canonical discriminant analysis. ANOVA results indicated that there were significant differences among sites and treatments with respect to species cover, stems and individuals. Pair-wise comparisons between treatment and control are treated below followed by a summary analysis using canonical discriminant analysis.

Shrubs: Russian Olive, Cottonwood, and Coyote Willow

The sites show a range of variation with respect to overall shrub species composition and cover, irrespective of treatment (tables 2-4) The I-40 site is strongly dominated by Russian olive with only minor amounts of willow (table 2).

Table 2—Russian olive means and standard deviations by site and treatment for percent cover, average number of individuals and average number of stems per quadrat. The significant difference row indicates if the LSD showed a significant difference between the treatment and the control of the given site for species means. * = significantly different; NS = not significantly different.

Russian olive	I-40 control	I-40 treatment	I-25 control	I-25 treatment	Belen control	Belen treatment	Tingley side bar	Tingley island bar
Cover								
Mean	64.1	25.9	53.7	21.6	13.7	6.77	0.002	3.97
Standard deviation	41.1	29.2	35	23.5	27.9	15.2	0.009	16.6
Significant pair difference	*	*	NS	NS				
Number of individuals								
Mean	0.8	0.667	0.717	0.183	0.15	0.2	0.033	0.033
Standard deviation	1.13	1.0	0.838	0.359	0.494	0.596	0.183	0.183
Significant pair difference	NS	*	NS	NS				
Number of stems								
Mean	2.83	4.87	7.9	2.53	0.867	1.2	0.033	0.033
Standard deviation	4.19	8.79	9.14	6.42	2.37	3.69	0.183	0.183
Significant pair difference	NS	*	NS	NS				

Table 3—Coyote willow means and standard deviations by site and treatment for percent cover, average number of individuals and average number of stems per quadrat. The significant difference row indicates if the LSD showed a significant difference between the treatment and the control for the given site for species means. * = significantly different; NS = not significantly different.

Coyote willow	I-40 control	I-40 treatment	I-25 control	I-25 treatment	Belen control	Belen treatment	Tingley side bar	Tingley island bar
Cover								
Mean	0.585	0.5	19.7	25.4	58.8	38.6	68.4	50.2
Standard deviation	3.2	1.9	31	27.9	23.3	26.7	27.6	29.9
Significant pair difference	NS	NS	*	*				
Number of individuals								
Mean	0.017	0.033	1.1	1.15	5.3	3.43	4.22	5.78
Standard deviation	0.091	0.183	1.32	1.5	2.14	1.92	2.87	3.18
Significant pair difference	NS	NS	*	*				
Number of stems								
Mean	0.133	0.133	9.2	10.8	15.6	13.4	19.1	19.3
Standard deviation	0.73	0.73	14.9	13.7	9.91	10.4	14.5	13.5
Significant pair difference	NS	NS	NS	NS				

Table 4—Cottonwood means and standard deviations by site and treatment for percent cover, average number of individuals and average number of stems per quadrat. The significant difference row indicates if the LSD showed a significant difference between the treatment and the control for the given site for species means. * = significantly different; NS = not significantly different.

Cottonwood	I-40 control	I-40 treatment	I-25 control	I-25 treatment	Belen control	Belen treatment	Tingley side bar	Tingley island bar
Cover								
Mean	9.33	1.47	0	0	12.8	3.55	2.52	0.752
Standard deviation	24.4	7.58	0	0	18.1	12.4	9.07	1.63
Significant pair difference	*	NS	*	NS				
Number of individuals								
Mean	0.067	0.033	0	0	0.5	0.133	0.083	0.4
Standard deviation	0.286	0.183	0	0	0.965	0.49	0.265	0.77
Significant pair difference	NS	NS	*	NS				
Number of stems								
Mean	0.167	0.067	0	0	1.13	0.3	0.133	0.4
Standard deviation	0.747	0.365	0	0	2.45	1.29	0.434	0.77
Significant pair difference	NS	NS	*	NS				

In contrast, the unmowed Tingley Beach site is dominated by coyote willow and lacks significant Russian olive (table 3). The I-25 site is also dominated by Russian olive, but has a significant component of willow intermixed in the canopy. Similarly, the Belen site is dominated by willow, but has a significant amount of Russian olive. There was an overall differential distribution of cottonwoods as well. They were well represented at the I-40 site, common at the Belen site, scattered at the Tingley Beach site, and absent at I-25 site. Similar site trends were also evident in terms of number of stems and individuals (tables 2-4).

Regardless of these site differences, there are still several within-site treatment effects that are apparent on a pair-wise basis. It appears that the mowing affected cottonwood more than the exotic Russian olive, and that coyote willow was least affected. Generally, the controls (unmowed) had higher shrub cover, particularly for Russian olive and cottonwood, and less so for willow.

For Russian olive, cover significance declined between 50-60 percent relative to the unmowed transects on the I-40 site and I-25 sites where it was most abundant to begin with, and the same trend is indicated at the Belen site (table 2). But there was a differential response with respect to stems and individuals; on the I-40 site despite the reduction in cover, the number of individuals did not significantly decline and there is a suggestion that the number of stems may have increased with mowing. On the I-25 site Russian olive individuals and stems did decline, but this confounded by the intense burn that occurred on the site in 1994. The combination of mowing and burning may negatively impact Russian Olive.

Coyote willow cover was not as strongly affected by mowing. Treatment effects were only significant at the Belen site, with a decline 35 percent in willow cover, and a commensurate decline in the number of individuals on mowed transects, but the number stems actually increased. The I-25 site had a fair amount of willow, but no treatment effect was detectable. There was also a minor difference at the untreated Tingley Beach sites with the island showing slightly less cover for willow, but more stems. More than likely this reflects the younger age class of willows on the island with a greater number of stems, but less canopy for their size.

Cottonwood showed significant declines (70-90 percent) with mowing at both the Belen and I-40 sites. The same trend was evident for stems and individuals, but was only significant at the Belen site. No cottonwoods were present on the I-25 site, most likely due to the high mortality following the 1994 fire. The Tingley site cottonwoods showed a similar pattern to the willows, with a significant increase in stems on the island site and a corresponding trend of lower cover, which was probably related to stand age.

Herbaceous Cover and Diversity

On a site basis, there were several differences with respect to understory species dominance. Meadow fescue was abundant and dominated the Tingley Beach site, and was uncommon or absent at the other sites. There was also significantly higher cover of fescue on the island bar than on the side bar. Alkali muhly was a common associate, but never dominant. In contrast, alkali muhly dominated the Belen site along

with Nebraska sedge. Alkali muhly was also a dominant on the I-25 site, but this time co-occurring with inland saltgrass, with a significant component of heath aster. Alkali sacaton was the primary dominant on the I-40 site with both inland saltgrass and alkali muhly as common co-dominants, and on the controls, Baltic rush and Nebraska sedge.

On a pair-wise analysis of treatment affects, there was a trend towards increasing grass cover with mowing (table 5). On the I-40 site, Alkali sacaton showed a strong, significant increase in cover and dominance with mowing; on the control sites it was a co-dominant with cover comparable to other graminoid species. Baltic rush tended to decrease on mowed transects, significantly so at the I-40 site. Nebraska sedge, although it showed a decrease on mowed transects at I-40, increased on mowed transects at Belen, and there was no overall significant difference between treatment and control. Inland saltgrass response was also equivocal; it dramatically increased with mowing on the I-25 site, but declined somewhat at the I-40 site. The common forb, heath aster, was most abundant at the I-25 site and showed a significant decrease on mowed transects. On other sites it was not abundant enough to detect a treatment effect.

With respect to diversity measures, there was only a slight indication of direct treatment effect with decreasing species richness (total number of species) with mowing (table 6). This was mostly evident at the Belen site, and in the comparison of all sites to the Tingley Beach site. The never-mowed Tingley Beach site had the highest species richness over all sites. Only the Belen controls had a similar number of species. With respect to the number of very abundant species (N1) and abundant species (N2), no strong patterns emerge. There is an indication that the I-40 site was not only lower in diversity, but tended to have fewer co-dominants as indicated by the lower N1 and N2 values in comparison to other sites. But overall, the ratio N2 to N1 as represented by E5 indicates that abundance was relatively evenly distributed among all sites except Tingley Beach Site. This may reflect the strong dominance at this site by willows with a diverse but lower cover understory.

An Overview with Canonical Discriminant Analysis

The canonical discriminant analysis of shrub cover of Russian olive, cottonwood, coyote willow and salt cedar demonstrated the overall differences between sites and treatments. Only the first two canonical functions were significant, with eigenvalues greater than 1.0, and accounted for 92.3 percent of the variation (table 7). Figure 11 is a graphical representation of the distribution of centroids (collective means) of the site/treatment combinations with respect to these first two functions. Function 1 accounts for 77.2 percent of the variation and is primarily responsible for separating sites. The canonical structure indicates that Russian olive and coyote willow cover are the primary discriminators along this axis, with salt cedar as a minor element (table 7). There is some overlap between I-25 Control and I-40 treatment (they have similar covers for Russian olive), and between Belen Control and Tingley Beach Island (they have similar willow cover). Function 2 serves to separate treatment and controls, but only accounts for

Table 5—Average herbaceous and graminoid percent cover per quadrat by site and treatment. The significant difference row indicates if the LSD showed a significant difference between the treatment and the control for the given site for species means. * = significantly different; NS = not significantly different.

Grasses and forbs	I-40 control	I-40 treatment	I-25 control	I-25 treatment	Belen control	Belen treatment	Tingley side bar	Tingley island bar
Heath aster								
Mean	0	0	27.4	15.6	0.333	0.002	0.25	0.417
Standard deviation	0	0	31.4	17.6	1.43	0.009	0.763	1.48
Significant pair difference	NS	*	NS	NS				
Inland saltgrass								
Mean	10.9	2.22	5.52	20.7	0	0	0	0
Standard deviation	26.5	8.17	10.6	20.4	0	0	0	0
Significant pair difference	*	*	NS	NS				
Meadow fescue								
Mean	0	0	0	0	0.967	0	5.05	26.6
Standard deviation	0	0	0	0	5.29	0	17.5	33.3
Significant pair difference	NS	NS	NS	*				
Alkali muhly								
Mean	3.5	6.68	21.1	22.4	25.8	30.5	2.89	2.42
Standard deviation	16.2	17.4	20.4	17.2	18.7	27.9	8.53	4.71
Significant pair difference	NS	NS	NS	NS				
Alkali sacaton								
Mean	7.6	34.6	1.25	0	0	0.167	0.337	0
Standard deviation	18.1	32.7	4.44	0	0	0.634	1.43	0
Significant pair difference	*	NS	NS	NS				
Baltic rush								
Mean	13.1	0	0	0	3.02	0.002	0.417	0
Standard deviation	25.1	0	0	0	10.5	0.009	1.48	0
Significant pair difference	*	NS	NS	NS				
Nebraska sedge								
Mean	3.5	0	0	0	16.2	20.1	0	0
Standard deviation	15.9	0	0	0	22.4	34.7	0	0
Significant pair difference	NS	NS	NS	NS				

Table 6—Average number of species, Hill's evenness and diversity index per transect by site/treatments.

Hills diversity indices	I-40 control	I-40 treatment	I-25 control	I-25 treatment	Belen control	Belen treatment	Tingley side bar	Tingley island bar
N0 (Number of Species)	11.0	9.67	13.7	13.3	18.0	13.7	19.7	18.3
N1 (very abundant species)	5.15	5.78	8.27	8.29	9.55	6.39	5.13	7.50
N2 (abundant species)	4.30	5.09	6.92	7.34	8.19	5.26	3.38	5.45
E5 (evenness)	0.799	0.856	0.811	0.875	0.843	0.784	0.533	0.686

Table 7—Shrub cover canonical between group correlation structure for the two significant canonical discriminant analysis (CDA) functions.

Species	CDA function 1	CDA function 2
Russian Olive	-0.91	0.39
Cottonwood	0.03	0.71
Coyote Willow	0.97	0.22
Salt Cedar	0.58	-0.25
Eigenvalue	1.39	0.27
% of variation	77.2	15.1
Cumulative %	77.2	97.3

Shrubs

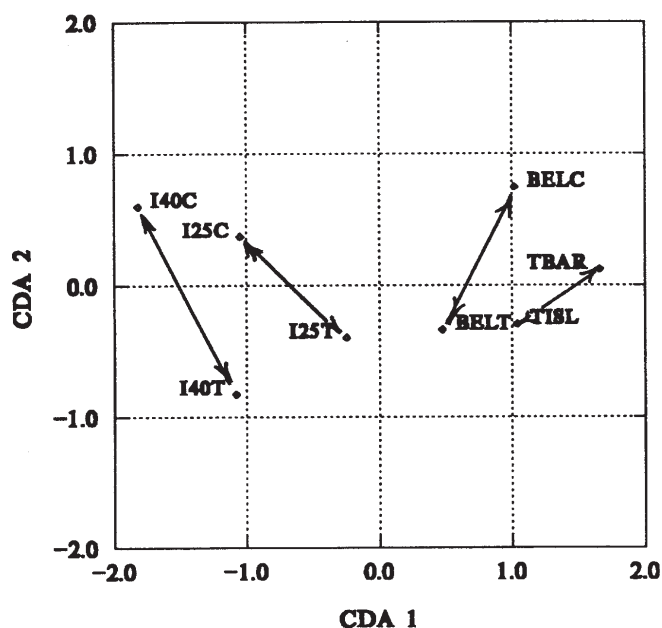


Figure 11—Shrub canonical discriminant analysis (CDA) site/treatment centroid position on functions 1 and 2. I40C = I-40 control transects; I40T = I-40 treatment; TRAR = Tingley side bar; TISL = Tingley island bar; I25C = I-25 control; I25T = I-25 treatment; BELC = Belen control; BELT = Belen treatment.

Forbs and Grasses

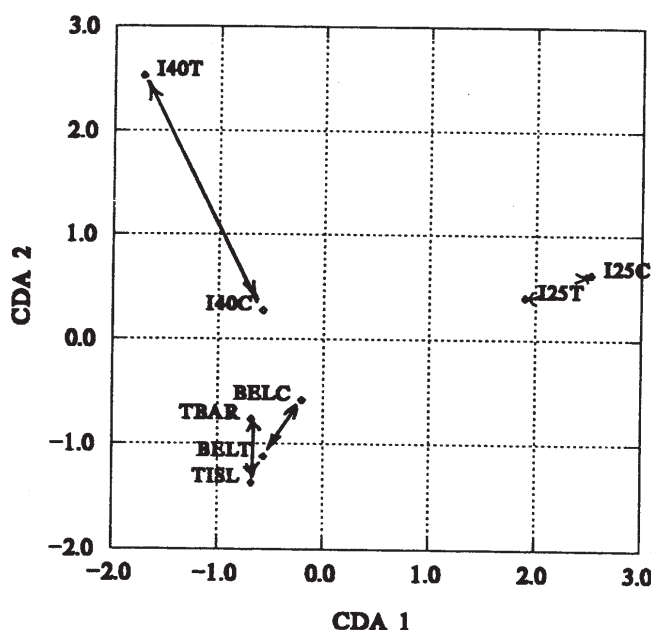


Figure 12—Forb and graminoid canonical discriminant analysis (CDA) site/treatment centroid position on functions 1 and 2. I40C = I-40 control transects; I40T = I-40 treatment; TRAR = Tingley side bar; TISL = Tingley island bar; I25C = I-25 control; I25T = I-25 treatment; BELC = Belen control; BELT = Belen treatment.

15.1 percent of the variation. The strong difference between treatment and control at the I-40 and Belen sites is evident and driven primarily by the difference in cottonwood cover and secondarily by Russian olive. Neither willow nor salt cedar appear to be very important discriminators.

The discriminant analysis based on understory herbaceous cover is less clear. There were three significant functions derived from the basis of 16 species' cover values. The I-25 site is clearly isolated along the positive end of the function 1 axis (fig. 12). This is primarily a result of positive correlations for heath aster and vine mesquite (*Panicum obtusum*), and to a lesser degree for Canadian horsetail (*Conyza canadensis*), Indian grass (*Sorghastrum nutans*) and alkali muhly. Conversely, the I-40 treatment is found on the far negative end of the axis primarily as a result of high alkali muhly and alkali sacaton cover. The I-40 treatment is further separated along the second axis by alkali sacaton, and to a lesser degree Russian thistle (*Salsola kali*) (table 8).

Axis 2 also isolates the Belen and Tingley Beach sites on the negative side as a function of negative loading on meadow fescue, smooth horsetail (*Equisetum arvense*) and Nebraska sedge. The only noticeable treatment effect in functions 1 and 2 is for the I-40 site, and it is primarily driven by high grass cover on the treatments. There are a few limited treatment effects apparent along canonical axis 3 for the Belen site and I-25 site (fig. 13). These differences are driven

Table 8—Herbaceous and graminoid cover canonical between group correlation structure for the three significant canonical discriminant analysis (CDA) functions.

Species	CDA 1	CDA 2	CDA 3
Cuman ragweed	0.58	-0.21	0.27
Indianhemp	-0.16	-0.37	0.72
Heath aster	0.94	0.25	-0.09
Seepwillow	-0.43	0.02	0.62
Nebraska sedge	-0.2	-0.42	0.86
Thymeleaf sandmat	-0.46	0.16	-0.35
Canadian horsetail	0.73	-0.18	-0.34
Inland saltgrass	0.57	0.31	-0.03
Smooth horsetail	-0.09	-0.47	-0.69
Meadow fescue	-0.23	-0.5	-0.68
Baltic rush	-0.18	0.04	0.03
Alkali muhly	0.48	-0.14	0.81
Vine mesquite	0.93	0.23	-0.04
Russian thistle	-0.49	0.81	-0.01
Indian grass	0.56	0.27	0.18
Alkali sacaton	-0.51	0.85	-0.02
Eigenvalue	1.88	1.43	1.16
% of Variation	33.6	25.5	20.8
Cumulative %	33.6	59.1	80

Forbs and Grasses

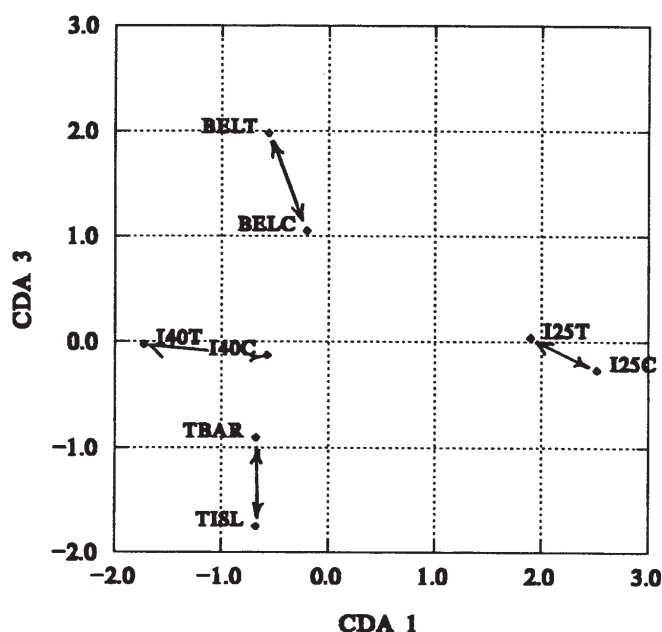


Figure 13—Forb and graminoid canonical discriminant analysis (CDA) site/treatment centroid position on functions 1 and 3. I40C = I-40 control transects; I40T = I-40 treatment; TBAR = Tingley side bar; TISL = Tingley island bar; I25C = I-25 control; I25T = I-25 treatment; BELC = Belen control; BELT = Belen treatment.

primarily by differential cover of Nebraska sedge and alkali muhly. For the Tingley Beach site, there was a slight difference between the island and the sidebar, primarily driven by relative meadow fescue and smooth horsetail cover.

Discussion

Mowing has a differential impact on various species, which is highly apparent on some cases regardless of specific site conditions. The greatest negative effect was on the native cottonwood, where there were significant declines on some sites with respect to cover, stems and individuals. Mowing also reduces the exotic Russian olive cover, but not as effectively as it reduces the cottonwood. In contrast to cottonwood, Russian olive seems to respond well in some cases by resprouting and creating vigorous multi-stemmed individuals. The native coyote willow does not seem to be very affected by mowing or not mowing. However at Belen, the one mowed site strongly dominated by willow, willow cover and number of individuals was reduced by about a third. Since coyote willow is a disturbance-adapted species it is not surprising that it shows less effect from the mowing than the other two later successional stage species, and that it may even respond positively to mowing. What is clear is that regardless of which other shrubs were dominant, cottonwood was always the shrub most negatively affected by mowing.

The general trend for the grass cover to increase on mowed transects is not surprising, since mowing, by reducing the shrub cover, increases the amount of light available to the understory. However, in many cases the increase in understory cover on mowed transects was not very great, and is rarely statistically significant. For the one common forb and the common rush and sedge, cover actually decreased on mowed transects, in two cases significantly so. The rush and the sedge are both native wetland obligate species, and their decrease could indicate a negative impact on wetland quality as a result of the mowing.

Mowing may be having a negative effect on overall species richness as indicated by the high species richness at the unmowed Tingley sites and by the tendency for unmowed transects to have higher average species richness than mowed transects at the same site. The dominant shrub species at a site also appears to be a factor in species richness, as species richness was lower on those sites with higher Russian olive cover (I-25 and I-40).

Evenness appears to increase on mowed transects, at least at the two sites dominated by Russian olive (I-25 and I-40). However, at the Belen site the unmowed transects had higher species evenness. The never-mowed Tingley Beach site had the highest species richness but the lowest species evenness; this indicates that mowing is increasing species evenness by reducing less-common species and favoring an even distribution of common ones.

Hill's N1 diversity index measures species diversity by combining species richness and evenness to produce an estimate of the number of abundant species. Since it combines richness and evenness and since these showed opposite trends, it is not surprising that the sites intermediate on both were the ones that showed the highest diversity. In fact, the sites highest in average Hill's N1 diversity index, I-25 and Belen, were also the ones intermediate not only in species richness and evenness, but also in dominant shrub species.

The greatest difference in exotic versus native species is more related to the differences between sites, rather than to direct treatment effects. The difference between sites is especially marked when comparing the I-40 and I-25 sites to the Belen and Tingley sites; the first two being strongly dominated by Russian olive and the second two by coyote willow. The differences between these sites may be due to differences in soil moisture and possible flooding disturbance. The two willow sites may be lower in elevation and thus flooded more frequently and have wetter soils at depth. Furthermore, the I-25 site was burned in the spring of 1994, providing an additional variable that may be affecting species composition and abundance.

The conclusions drawn here are based on a very limited sample of sites and replications within sites, and on the basis of only one reading after three years of treatment. Continued, effective and uniform treatment may enhance differences in the future. Adding additional sites with treatments will also help further isolate environmental characteristics from treatment effects. At the same time, there should be more detailed comparative studies on soils, landforms, hydrology and fire history done in order to make effective and definitive statements about the causes of differences in species composition, dominance and the overall structure in relation to mowing.

Acknowledgments

Support for this work was provided through Cooperative Agreement No. 6-FC-40-19890 between the Bureau of Reclamation, Albuquerque Office and the New Mexico Natural Heritage Program, Biology Department, University of New Mexico, Albuquerque, NM.

References

- Ludwig, J.A., and J.F. Reynolds. 1988. *Statistical Ecology: A Primer on Methods and Computing*. John Wiley and Sons, New York.
- SAS/STAT User's Guide. Version 6, Fourth edition. 1990. SAS Institute Inc. Cary, North Carolina, U.S.A.
- SCS. 1995. *Plants Database*. USDA Soil Conservation Service, Washington D.C.
- Sokal, R.R., and F.J. Rohlf. 1981. *Biometry: The Principles and Practice of Statistics in Biological Research*. W.H. Freeman and Co., San Francisco.

Establishment of Rio Grande Cottonwood Seedlings Using Micro-irrigation of Xeric Flood Plain Sites

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Abstract—Flood control, irrigation structures, and flow control practices on the Middle Rio Grande have prevented the deposition of sediments and hydrologic conditions conducive to the germination and establishment of Rio Grande cottonwood (*Populus fremontii* S. Wats.). The Los Lunas Plant Materials Center has been investigating the use of micro-irrigation systems on xeric flood plain sites to promote regeneration from natural cottonwood seed dispersal. The initial study showed no establishment benefits resulting from organic-rich substrates versus indigenous mineral surface soil. In the second study, three emitter types (53 L/hr spitter, 14 L/hr spitter, 24 L/hr bubbler) produced mean wetted soil surface areas of 2.7, 0.58, and 0.33 m², respectively, and median seedling counts per plot of 70, 29, and 16, respectively. In the initial study, the plots with the greatest cottonwood seedling density after one growing season contained 22 seedlings/m² (15 cm height) without weed control (infested with *Kochia scoparia* (L.) Roth) and 86 seedlings/m² (69 cm height) with weed control. Primary weed pests in the second study were *Tamarix*, *Cenchrus*, and *Artemisia* species; weed infested plots had 35 to 45 percent fewer seedlings than plots with weed control after one growing season. Technology development will concentrate on reducing labor costs for irrigation operation and weed control, the major costs in applying this technology. Micro-irrigation technology offers an alternative method of managed cottonwood regeneration for sites where flood irrigation or pole plantings are not practical because of economic, engineering, water use, or jurisdictional constraints.

Flood control and irrigation structures as well as flow control practices on the Middle Rio Grande have drastically altered sediment deposition and soil moisture conditions on the flood plain. These changes have prevented the necessary soil conditions and water regimes required for the regeneration of Rio Grande cottonwood (*Populus fremontii* S. Wats.) and other riparian trees and shrubs on flood plain sites remote from the river channel (Whitney 1996). The lack of regeneration of the dominant native trees, the spread of

exotic woody species (*Tamarix* spp. and *Elaeagnus angustifolia* L.), and the perturbation in ecosystem function attributable to the lack of flooding has resulted in a rapid decline in the health of the riparian cottonwood forest (Dick-Peddie 1993, Crawford and others 1996).

The Los Lunas Plant Materials Center (USDA-NRCS) has been investigating techniques to reestablish the dominant native trees and shrubs in these degraded riparian cottonwood forests for the past 15 years. These efforts have been made in cooperation with federal (Army Corps of Engineers, Bureau of Reclamation, Bureau of Land Management, Fish and Wildlife Service, Bureau of Indian Affairs), state (Park and Recreation Division, Game and Fish Department) and local agencies (Albuquerque Open Space Division). Throughout the 1980's and early 1990's, these efforts focused on enhancing the success of pole plantings of Rio Grande cottonwood, Goodding's willow (*Salix gooddingii* Ball), and coyote willow (*Salix exigua* Nutt.). Recent studies have investigated the use of pole plantings to establish important shrub species of the cottonwood riparian forest including false indigo (*Amorpha fruticosa* L.), New Mexico olive (*Forestiera neomexicana* Gray), and seepwillow (*Baccharis* spp.). In the past several years, we have redirected much of our research into investigating methods to establish Rio Grande cottonwood seedlings by supplementing surface soil moisture using micro-irrigation techniques.

The existing riparian cottonwood forest disseminates massive quantities of viable seed within the flood plain of the Rio Grande. Soil moisture conditions conducive to the germination and early survival of these seedlings are generally only found on banks and sandbars. Most of these seedlings are washed away by high water flows the following spring (Whitney 1996). We investigated the concept of providing a precise application of water to xeric flood plain sites remote from the river channel to create an optimum seedbed for seed adherence, germination, and seedling survival until the sapling roots reach the capillary fringe above the water table. If this technique proves feasible, it may substantially reduce the costs of forest regeneration in relation to pole planting, which typically costs from 25 to 40 dollars per pole (Los Lunas Plant Materials Center 1997). Costs of pole plantings include not only the immediate expense of dormant pole cuttings and installation, but also the costs involved with pest damage control (for example, tree guard installation and cottonwood leaf beetle suppression). However, seedlings established using micro-irrigation will also require cottonwood leaf beetle control. In addition to the potential economic incentives, the use of micro-irrigation to

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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establish a cottonwood riparian forest from natural seed dispersal will impart much greater genetic diversity than is achieved by planting poles derived from clones in production nurseries.

This paper addresses our initial proof of concept studies which sought to determine: 1) the effect of organic-rich substrates on seedling survival and growth; 2) the influence of different types of micro-irrigation emitters on the area of wetted soil surface and the number of seedlings established; 3) the effect of weed competition on seedling density and height growth; 4) the amount of irrigation water applied during the germination and early establishment phase; and, 5) irrigation system design and costs of a hypothetical large scale cottonwood regeneration project. Discussion of future investigations concentrate on 1) reducing costs for irrigation operation and weed control, 2) simplifying the micro-irrigation system, and 3) minimizing water use.

1996 Study—Soil Surface Treatments

Observations of volunteer cottonwood seedlings in the bare-root nursery at the Plant Materials Center indicated seedling establishment occurred on organic-rich soil-less mixes with micro-sprinkler irrigation every 6 hours. These observations prompted trials of surface materials that might promote seedling establishment by increasing cottonwood seed adherence and providing optimum moisture during germination and early growth. The cost of soil-less mix compelled the testing of less expensive organic substrates and 2 different thickness' of these surface treatments.

Methodology

The study was conducted at the Rio Grande Nature Center on disturbed sandy loam soils having a severe infestation of summer cypress (*Kochia scoparia* (L.) Roth). Plots (each 2.4 m x 3.0 m) were dug to a depth of 0.15 m with the bucket of a front end loader tractor. The plots were ripped an additional 0.5 m in depth to break a caliche layer. The plots were then back-filled with indigenous mineral soil, mulch, or soil-less mix to provide 2 depths of organic substrates. The surface treatments were as follows: 1) indigenous soil, 2) shredded residential green waste 5 cm thick, 3) shredded residential green waste 15 cm thick, 4) soil-less mix (component volume ratio 6:3:1 pumice:peat:composted bark) 5 cm thick, and 5) soil-less mix 15 cm thick. The plots were replicated in 3 blocks with the treatments in random order. Regardless of the thickness of the soil treatment, the surface of plots was level with the surrounding terrain so surface runoff would not flow onto the plots.

Each of the 15 plots was irrigated with one variable flow micro-sprinkler having a maximum flow rate of 87 L/hr, a 90 degree spray pattern, and a wetted plot area of 5m². The 15 micro-sprinklers were connected to lateral surface pipelines of 0.75 inch polyethylene tubing with 0.25 inch micro-tubing. Irrigation frequency and duration were controlled using a battery operated irrigation controller. The water source was an existing shallow well with a photo-voltaic powered submersible pump.

Irrigation of the plots was started on May 3, 1996 to allow germination of weed seed. A 2 percent solution of glyphosate ('Roundup') was applied twice to reduce weed populations prior to cottonwood seed dissemination. At this location, seed dispersal began May 31, 1996 and continued until July 20, 1996. For 5 weeks, 23 L of water were applied 4 times daily at 3 hr intervals to each plot (i.e., 92 L/day per plot or 3.1 gal/week per square foot). On July 9, 1996, the irrigation schedule was changed to a weekly application of 870 L per plot in a single ten hour period (i.e., 4.3 gal/week per square foot) until November 1, 1996 when irrigation was stopped. In April 1997, irrigation resumed with 1500 L per plot applied once a month in a single 3 day period (i.e., 1.7 gal/week per square foot).

On July 2, 1996, hand weeding of one experimental block of 5 treatments was stopped to examine the effect of weed competition on cottonwood establishment; these plots are denoted as NWC (no weed control). The other plots, WS (weed suppression), were hand weeded weekly for the remainder of the 1996 growing season. A pre-emergent herbicide (0.17 percent pendimethalin, 'Stomp') was applied to the WS plots in March 1997 after spot spraying volunteer grass seedlings with a 2 percent glyphosate solution. In addition, the WS plots were hand weeded in July and August 1997. In 1997, the seedlings were sprayed with a 0.001 percent solution of cyfluthrin ('Tempo II') monthly from June to October to control cottonwood leaf beetle. Cottonwood seedling density was measured in November 1996 and 1997 using a meter square frame placed in the center of each plot; seedling height of 5 to 10 seedlings per plot was also recorded.

Results and Discussion

By July 1, 1996, the larger seedlings in the indigenous soil treatment were in the four to five leaf stage (5 to 8 cm in height) and had root lengths of up to 10 cm. In contrast, the seedlings in the shredded green waste and soil-less mix treatments were stunted with heights of 2 to 3 cm, root lengths less than 8 cm, and red to yellow discoloration. On July 2, each WS plot was fertilized by applying 50 L of 100 mg/L nitrogen (10 kg/ha) as a soluble fertilizer solution ('Peters 20-10-20 Peat Lite Special' with minor- and micro-nutrients). The NWC plots were not fertilized.

After the first growing season, the WS treatments having the greatest seedling density and tallest seedlings were the indigenous soil (77 seedlings/m² and 0.75 m) and the shredded green waste 5 cm thick (86 seedlings/m² and 0.69 m) as shown in table 1. After the second growing season, these same treatments had the tallest seedlings; the seedling density of the indigenous soil treatment (25 seedlings/m²) was not significantly different than the other treatments except for the 15 cm thick soil-less mix (11 seedlings/m²). These data show no benefit in seedling growth or establishment as a result of the organic-rich surface treatments. The micro-irrigation schedule apparently provided equivalent seed adherence and surface moisture for the establishment of cottonwood seedlings on indigenous mineral soil negating any perceived benefits of the organic-rich substrates.

The seedling density after the second growing season ranged from 24 to 33 percent of the density after the first

Table 1—Rio Grande cottonwood seedling height and seedling density on micro-irrigated plots at the Rio Grande Nature Center. Means and standard errors reported for plots with weed suppression and fertilizer application; plots with no weed control or fertilizer application were not replicated.

	Surface treatments				
	Indigenous soil	Soil-less mix 5 cm	Soil-less mix 15 cm	Green waste 5 cm	Green waste 15 cm
Plots with weed suppression and fertilizer application					
Mean seedling height (m)					
After first growing season	0.75	0.39 c	0.23 c	0.69	0.47 b
(Standard error)	(0.01)	(0.02)	(0.03)	(0.08)	(0.04)
After second growing season	1.75	1.28	0.77 b	1.61	1.35 b
(Standard error)	(0.10)	(0.24)	(0.14)	(0.22)	(0.05)
Mean seedling density (no./m ²)					
After first growing season	77	63 c	15 c	86 a	57 b
(Standard error)	(2)	(1)	(5)	(4)	(4)
After second growing season	25	21	11 b	21	19
(Standard error)	(2)	(2)	(2)	(3)	(8)
Plots with no weed control and no fertilizer application					
Seedling height (m)					
After first growing season	0	0	0	0.15	0.15
After second growing season	0	0	0	0.51	0
Seedling density (no./m ²)					
After first growing season	0	0	0	22	4
After second growing season	0	0	0	7	0

a Mean significantly different from indigenous soil treatment at $P \leq 0.10$ and $P > 0.05$.

b Mean significantly different from indigenous soil treatment at $P \leq 0.05$ and $P > 0.01$.

c Mean significantly different from indigenous soil treatment at $P \leq 0.01$.

growing season for treatments with high initial densities. The competition for light, nutrients, and water resulted in a substantial natural thinning process.

Those plots with no weed control or fertilizer additions showed very little if any survival after the first growing season. Only the shredded green waste plots showed negligible survival and growth after the first growing season. The coarse texture of the shredded material might have reduced weed establishment allowing some cottonwood seedlings to survive.

This initial experiment clearly showed that indigenous mineral soils could provide a satisfactory substrate for cottonwood seedling establishment if surface soil moisture is precisely controlled. At this site, weed competition and low fertility favored weeds over cottonwoods even with non-limiting soil moisture.

1997 Study—Evaluation of Micro-irrigation Devices

The 1996 study showed that micro-sprinklers could provide sufficient control of surface moisture to allow cottonwood seedling establishment. The large wetted area produced by these sprinklers resulted in a large dense thicket of seedlings. Smaller wetted areas would require less natural thinning by competition, reduce weed control efforts, and reduce the amount of water to establish cottonwoods on one spot (with the eventual thinning to one tree). Therefore, the goal of the 1997 study was to determine the number of

seedlings established in wetted areas created by 3 micro-irrigation emitter types. In addition, the 1997 study site was more representative of typical restoration locales which lack existing wells and pumping equipment and comprise large disturbed areas.

Methodology

The 0.4 ha site is located just downstream of the confluence of the Calabacillas Arroyo on the west bank of the Rio Grande within the Rio Grande State Park (administered by the Albuquerque Open Space Division). Approximately three-fourths of site was enclosed with snow fence to limit disturbance by public activity. The remaining 0.1 ha was not fenced and was adjacent to a horse and walking path. The site characteristics include loamy sand soil and limited vegetative cover primarily of *Artemisia* spp. and *Cenchrus longispinus* (Hack) Fern. (sandbur) with little woody vegetation except a few widely separated coyote willow thickets outside the study site.

A 5 m deep well was developed using a 2 inch well-point. A gasoline-powered centrifugal pump capable of providing 245 L/min at 40 psi and with a suction lift of 4.6 m supplied water to the irrigation system. The discharge was filtered (spin-clean filter) and supplied a 1.5 inch PVC header that spanned the length of the enclosure and extended into the unfenced area. The lateral lines (16 within the enclosure and 2 outside) consisted of 30 psi fixed pressure regulators connected to 0.75 inch polyethylene tubing with capped ends

to allow flushing. The emitters were attached to the laterals with 0.125 inch micro-tubing. The 3 emitter types were mini-flow spitters [Roberts Spot-Spitters,] (14 L/hr at 15 psi with a 90 degree spray pattern), medium-flow spitters (53 L/hr at 15 psi with a 160 degree pattern), and a lead-weighted bubbler (24 L/hr at 15 psi with a point source). Each lateral line had between 7 and 10 mini-flow spitters, 4 to 8 medium-flow spitters, and 2 to 3 bubblers for a total of 313 emitters (167 mini-flow, 95 medium-flow, and 51 bubblers). The percentage of water applied by each emitter type was calculated by multiplying the number of emitters by the flow rate; these percentages are 27 percent for mini-flow spitters, 59 percent for medium-flow spitters, and 14 percent for bubblers.

Before initiating the cottonwood establishment study, the study area was irrigated and sprayed biweekly with a 4 percent solution of glyphosate herbicide. Daily irrigation for cottonwood seed germination began June 16, 1997; for the next six weeks the irrigation system was operated during daylight hours at three hour intervals for a period of one half hour. After six weeks, the seedlings were irrigated for three hours once or twice a week depending on precipitation. During seed adherence and germination phase (i.e., first six weeks), from 115 to 190 m³ of water were applied each week (see fig. 1). In the establishment phase (next 12 weeks), from 10 to 45 m³ of water were applied each week. For the entire growing season, 1234 m³ (326,000 gal or 1 acre foot) of water were used in the study during a total application period of 145 hr.

All plots inside the fenced area were hand weeded by the irrigation system operator. On three occasions during the growing season, 8 days of labor were spent weeding the plots

inside the enclosure. The plots outside the fence were not weeded during the first growing season. Seedlings were sprayed monthly from August to October 1997 with 0.001 percent cyfluthrin ("Tempo II") to control cottonwood leaf beetle. The numbers of seedlings established in the 313 plots were counted in October 1997. For the medium-flow spitter plots, counts of greater than 100 per plot were recorded and analyzed as a count of 100.

Results and Discussion

At this location, cottonwood seed dispersal began the third week of June 1997. Initial seedling emergence was observed during the fourth week of June. After the first growing season, the mean seedling numbers per plot ($\pm$ standard error) for each emitter type were as follows: mini-flow spitters 32 ($\pm$ 19) seedlings per plot, medium-flow spitters 67 ($\pm$ 27) seedlings per plot, and bubblers 20 ($\pm$ 14) seedlings per plot (see table 2). The distribution of seedling numbers for the 3 emitters is presented in figure 2. The most common seedling count classes were 11 to 40 for the mini-flow spitters, 61 to 80 and >100 for the medium flow spitters, and 1 to 30 for the bubblers. Only two out of 313 plots lacked established seedlings in October 1997. The total seedling establishment within the study site after the first growing season exceeded 12,700.

The percentage reduction in seedling density resulting from no weed control was derived from mean seedling counts per plot (and median seedling counts per plot): 37 percent (44 percent), 38 percent (35 percent), and 42 percent (45 percent) for mini-flow spitters, medium-flow spitters, and bubblers,

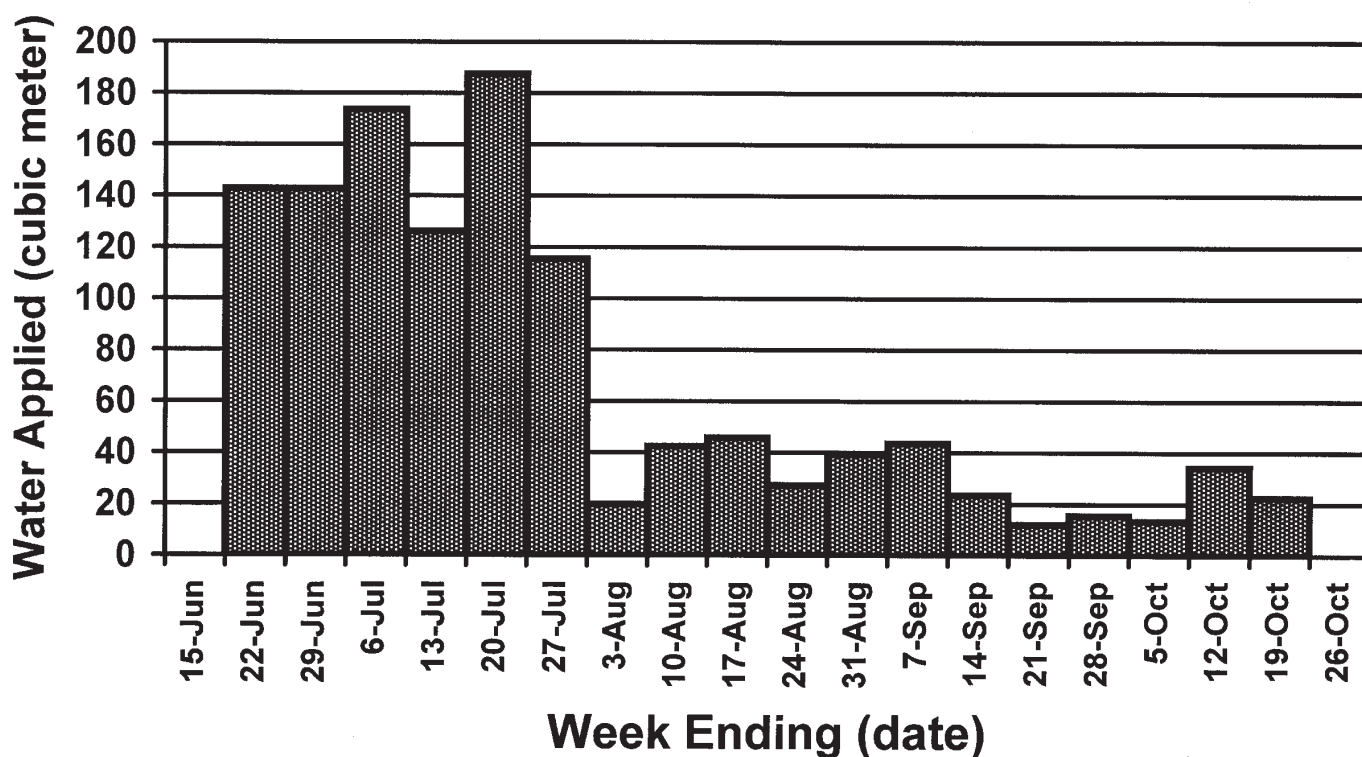


Figure 1—Irrigation water applied during the first growing season to the cottonwood seedling plots at the study site located on the west side of the Rio Grande below Calabacillas Arroyo. Water applied for the week preceding the date given.

Table 2—Number of Rio Grande cottonwood seedlings established per plot during the first growing season using 3 types of micro-irrigation emitters. Study site located on the west side of the Rio Grande below Calabacillas Arroyo.

Emitter type	Plot type a	Number of plots	Median	Mean	Standard error	Most common b	Seedling density c
		(no.)	(no./plot)	(no./plot)	(no./plot)	(no./plot)	(no./m ²)
Mini-flow spitter	All	167	29	31.7	19.1	11 to 40	50
	WS	148	32	33.1	19.4	nd	55
	NWC	19	18	20.8	12.2	nd	39
Medium-flow spitter	All	95	70	67.2 d	27.1 d	61 to 80, >100	26
	WS	86	72	69.7 d	26.4 d	nd	27
	NWC	9	47	43.2	20.4	nd	17
Bubbler	All	51	16	19.9	14.0	1 to 30	48
	WS	46	18	20.8	14.4	nd	55
	NWC	5	10	12.0	5.5	nd	30

a WS = weed suppression, NWC = no weed control, All = WS plus NWC plots.

b Three most common classes of seedling counts based on class intervals of 10.

c Median number per plot divided by estimated wetted area.

d Counts greater than 100 treated as 100 in mean and standard error analysis.

nd Not determined.

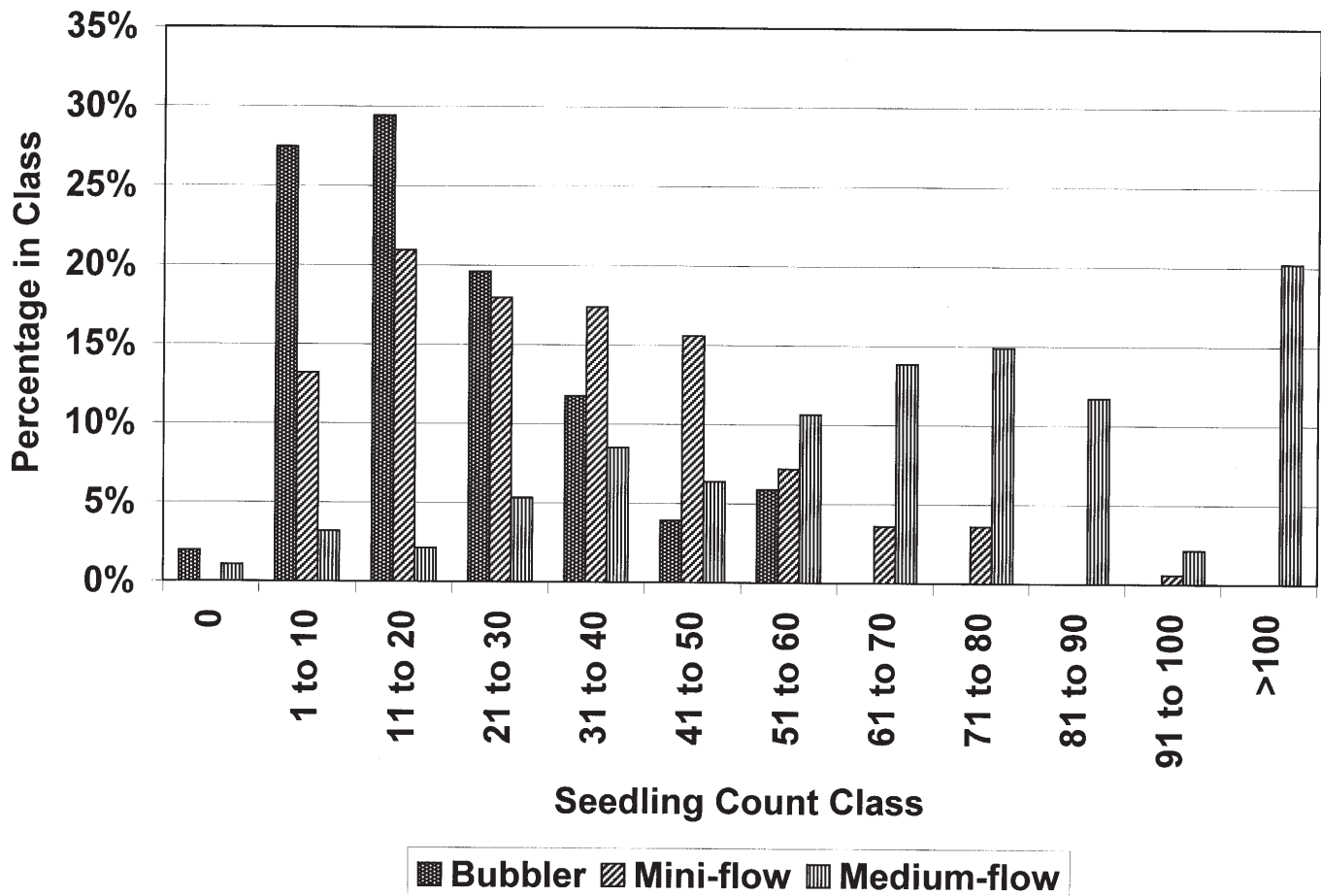


Figure 2—Rio Grande cottonwood seedling count distribution per plot for the 3 types of micro-irrigation emitters used at the study site located on the west side of the Rio Grande below Calabacillas Arroyo.

respectively. At the end of the first growing season many seedlings in the enclosure exceeded 0.3 m in height while some seedlings exceeded 0.6 m in height. With no weed control (outside the enclosure), the average seedling height was between 0.1 and 0.2 m. The plots with larger wetted areas appeared to have greater weed populations. These weeds in descending order of predominance were *Tamarix* spp., *Cenchrus longispinus*, and *Artemisia* spp. The reductions in survival and growth can not be related entirely to weed competition because the plots outside the enclosure suffered some disturbance by foot traffic and horses; this activity probably destroyed some seedlings and dislodged micro-tubing and emitters. The fencing prevented any obvious disturbance by people or pets to the plots receiving weed control.

The estimated wetted areas produced by the 3 emitter types are 2.71, 0.58, and 0.33 m² for medium-flow spitters, mini-flow spitters, and bubblers, respectively. The seedling density derived from these wetted areas are presented in table 2 using median seedling counts; the derived seedling densities are 55, 27, and 55 seedlings/m² for mini-flow spitter, medium-flow spitter, and bubbler plots with weed control. The corresponding water delivery rates are 24, 20, and 73 L/hr per m². This data might indicate that soil moisture could be limiting establishment on the medium-flow spitter plots. However, the calculated water delivery rate in the 1996 study at the Rio Grande Nature Center was 17 L/hr per m²; therefore, sub-optimum irrigation interval and duration are probably more responsible for reduced density than water delivery rate.

The findings of this study after the first growing season include: 1) the small wetted area provided by bubblers was sufficient to establish seedlings in almost all plots; 2) the bubblers seemed to support less weed invasion than the other emitters and had appreciably lower flow rates than the medium-flow spitter; 3) weed control is critical for effective establishment because it provides higher seedling densities and more vigorous seedlings; and, 4) fencing might be required near areas with foot or horse traffic.

The intent of this study was not to determine minimum irrigation requirements for seedling establishment. However, high estimates of water use can be projected from the irrigation application rates of these emitters. The mini-flow spitters with the smallest flow rates used 345 m³ of water to establish 5,300 seedlings; these data yield a water use of 65 L per seedling during the first growing season.

Economic Analysis of a Hypothetical Irrigation System

The high costs of most riparian restoration constrain the amount of disturbed areas that can undergo cottonwood regeneration. Pole planting costs of \$2500 to \$4000 per acre (\$6200 to \$9900 per ha) for cottonwood regeneration result from a recommended density of 100 trees per acre (250 trees per ha) assuming no mortality. The costs of irrigation and weed control used in the 1997 study can be extrapolated to an extended use of these methods for cottonwood regeneration of a large disturbed riparian area. The following analysis relies on many assumptions and can not account for many site characteristics, which could affect the engineering or the economics of the system. The intent is to provide a basis for evaluating the potential utility of the technology.

System Analysis of a Hypothetical Restoration Situation

The 6 hp pump used in the 1997 study is capable of providing 65 gpm (3900 gph) at 40 psi with a suction lift of 15'. A system composed solely of bubblers which deliver 3.6 gph at 10 psi could use up to 1080 bubblers (3900 gph/3.6 gph). The main line would have to consist of 2 inch ID pipe to accommodate 65 gpm. The mainline could be downsized to 1.5 inch ID toward the ends of the main line where flow rates would be less than 30 gpm. Spin clean filters would have to be installed in the pump discharge line to remove fine sand and silt from the irrigation water and minimize bubbler clogging. By assuming an acceptable density of cottonwood establishment of 100 trees per acre and assuming modest losses of young trees, 120 bubblers per acre could achieve the desired regeneration density. A total of 9 acres could be irrigated using these assumptions (1080 bubblers/120 bubblers per acre). By assuming a roughly rectangular disturbed area of 400 by 980 feet, a 2 inch main line 600 feet long would be required. Each lateral line could be 250 feet in length to provide a somewhat sinuous bubbler layout. If 30 bubblers were installed on each lateral (recommended maximum for uniform delivery with 0.5 inch ID tubing is 1.8 gpm), 36 lateral lines would be used for the 1080 bubbler allotment. If the bubblers are located within 10 feet of the lateral lines, the total lateral length (9000 feet) and bubbler corridor (20 feet) yield a potential irrigated area of 180,000 ft² or 46 percent of the total area. The micro-tubing that supplies each bubbler could be spaced about 8 feet apart on alternating sides of the lateral. If the length of micro-tubing varied between 5 and 10 feet with an average length of 7.5 feet, then 8100 feet of micro-tubing (0.125 inch ID) would be used.

The fixed costs of the irrigation system which are independent of the exact area or distribution system configuration include the 6 hp gasoline pump (\$900), materials and installation of the 2" well point with a galvanized steel pipe length of 20 feet (\$400), and miscellaneous parts including spin clean filters, suction and discharge hoses, and pressure gauge (\$300). The variable costs dependent on system configuration include the main line 2 inch ID (600 feet - \$180), main line fittings and fixed pressure regulators (36 lateral connections - \$400), lateral line 0.5 inch ID polyethylene tubing (9000 feet - \$675), lateral line fittings (36 laterals - \$100), micro-tubing 0.125 inch ID (9000 feet - \$160), and 1080 bubblers (\$450).

The labor, travel, and supply costs required by the 1997 study which would be applicable to a typical restoration project are presented as well as an estimated multiplying factor based on the total area of the hypothetical site being 9 acres:

- 1) Application of herbicide \$850 x 3 = \$2550
- 2) Plot mowing and raking \$725 x 5 = \$3625
- 3) Install irrigation system \$1075 x 2 = \$2150
- 4) Irrigate at 3 hour intervals for 6 weeks \$6400 x 1 = \$6400
- 5) Irrigate every 4 to 5 days for 12 weeks \$3600 x 1 = \$3600
- 6) Supplemental hand weeding excluding routine weeding by irrigation system operator \$1575 x 1 = \$1575

Conclusions

These cost estimates yield the following summary results for a 9 acre cottonwood regeneration project for the first growing season:

- 1) Fixed equipment costs \$1600
- 2) Variable irrigation supplies cost \$1965 or \$220/acre
- 3) Labor, travel, and weed control supplies cost \$19900 or \$2200/acre
- 4) Total \$23465 or \$2600/acre

The decisive factor in this analysis is the substantial costs resulting from weed control activities (33 percent of total) and irrigation operation (43 percent of total). The estimate of \$2600/acre falls in the low range of estimated pole planting costs. Costs in future years should be small because only repair of pumping equipment and irrigation system components will be required, much less intensive weed control will be needed, and irrigation frequency will be greatly decreased (for example, every 2 weeks in second year). Pole planting also requires future costs for pest control and possible tree guard removal. Any appreciable reduction in the cost of weed control and irrigation would imply that micro-irrigation could be a cost effective method of cottonwood forest regeneration.

Planned Studies

Minimizing Water Use and Irrigation Labor

The micro-irrigation approach to be investigated in 1998 focuses on the use of micro-porous tubing (Tyvek,) as the water emission device. This tubing operates at very low pressures (2 to 6 psi) and at very low delivery rates (for example one liter per day per foot of micro-porous tubing). These factors should allow continuous operation of the irrigation system during the germination phase and the use of a water storage tank, which would only require periodic refilling. The storage tank could be sized with a 3 day capacity to prevent the need for irrigation labor over week-ends. After the germination phase, the system could be manually turned on for a day, once or twice a week, to minimize the number of days the system needs attention.

Potential Weed Control Alternatives

Use of pre-emergence herbicides could be tested including: 1) particular chemicals with less adverse effects on cottonwood seedlings; 2) timing of application in relation to cottonwood germination and establishment; and, 3) rates of application. More effective nutrient additions by application of controlled release fertilizer might allow the cottonwood seedlings to better compete with weeds. The use of solarization could destroy the existing weed seed bank in the surface soil before cottonwood seed disseminates.

Conclusions

Micro-irrigation applied to xeric flood plain sites offers a method to establish cottonwood seedlings from natural seed dispersal. Micro-irrigation emitters providing small wetted areas (i.e., less than 1 m²) allow the establishment of sufficient seedlings for probable long term survival of at least one sapling per irrigated spot. Areas with pedestrian or horse traffic may require temporary fencing to prevent disturbance of the seedlings or the irrigation system. Weed control has been a significant factor in providing high survival and growth rates for cottonwood seedlings. Labor for weed control and irrigation operation are the highest cost activities for a cottonwood regeneration project based on the present micro-irrigation technology. Potential improvements in micro-irrigation emitters and system design could significantly reduce irrigation labor costs and minimize water used for seedling establishment. Better weed control strategies and application of controlled-release nutrients could reduce long-term weed control costs.

Micro-irrigation technology is an additional tool for land managers confronted with riparian restoration projects. The use of a particular restoration technique (for example, natural flooding, flooding resulting from human intervention, pole planting, or micro-irrigation) will depend on the hydrologic, edaphic, economic, engineering, and jurisdictional constraints of the restoration site.

References

- Crawford, Clifford S.; Ellis, Lisa M.; Molles, Manuel C.; Valett, H. Maurice. 1996. The potential for implementing partial restoration of the Middle Rio Grande ecosystem. In: Shaw, Douglas W. and Deborah M. Finch, tech coords. Desired future conditions for Southwestern riparian ecosystems: Bringing interests and concerns together. 1995 Sept. 18-22, 1995; Albuquerque, NM. General Technical Report RM-GTR-272. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 93-99.
- Dick-Peddie, William A. 1993. New Mexico vegetation, past, present, and future. University of New Mexico Press. 244 p.
- Los Lunas Plant Materials Center. 1997. Annual interagency riparian report, 1997, 11th edition. U.S. Department of Agriculture, Natural Resources Conservation Service, Los Lunas, NM. 31 p.
- Whitney, Jeffrey C. 1996. The Middle Rio Grande: Its ecology and management. In: Shaw, Douglas W. and Deborah M. Finch, tech coords. Desired future conditions for Southwestern riparian ecosystems: Bringing interests and concerns together. 1995 Sept. 18-22, 1995; Albuquerque, NM. General Technical Report RM-GTR-272. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 4-21.

Restoration and Monitoring in the Middle Rio Grande Bosque: Current Status of Flood Pulse Related Efforts

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Abstract—Extensive regulation of the Middle Rio Grande's natural flow regime, together with the effects of introduced tree species, landscape fragmentation, and increasing wildfires, are obstacles for any level of restoration of its native riparian forest (bosque). However, carefully monitored partial restoration is possible and greatly needed to prevent the bosque's serious decline. Monitoring can reveal temporal and spatial changes in the bosque's ecological dynamics. The Bosque Ecosystem Monitoring Program, which currently uses volunteers to synchronously record changes in biological populations and ecological processes at four sites in the middle valley, shows how this can be done. Partial restoration depends on well timed releases following heavy spring runoff. When these exceed bankfull stage, overbank flooding will (1) establish new cottonwood-willow stands at suitable locations and (2) enhance ecological maintenance of mature stands. Partial restoration can potentially involve alternative, non mutually exclusive manipulations of the river's hydrology within a given reach. A different approach, currently exemplified by the Albuquerque Overbank Project, involves lowering a bank so that natural flooding can establish new native vegetation. These conceptual and empirical efforts can build a foundation for bosque managers to assess where modified native bosque can persist, and can be the beginning of a comprehensive program to manage the riparian forest on a sustainable basis.

Regulation of the Rio Grande's flow regime in the 20th century has drastically altered the ecological dynamics of its riparian zone (Crawford and others 1993, 1996a). Historically, the river's channel shifted laterally across a generally wide floodplain (Biella and Chapman 1977, Gile and others 1981). Following wet winters, snowmelt in mountain watersheds would have produced overbank flooding downstream, which would have enabled seeds of native cottonwood, *Populus deltoides* ssp. *wislizenii*, and willow, *Salix* spp., to

germinate on newly deposited point bars and freshly scoured banks. Flooding, as inferred from Ellis and others (1998, Molles and others 1998) would also have enhanced decomposition and mineralization of wood and leaf litter on the forest floor, making nutrients available for uptake by already established bosque vegetation (Ellis and others 1998). Thus the basin's hydrology, conditioned by climate (Molles and others 1992), would have brought about a changing mosaic of bosque stands in varying states of development throughout the Holocene (Crawford and others 1996a).

The present landscape of the basin is very different, even along the so-called Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir, where one of the most extensive native riparian forests in the southwestern United States still exists (Howe and Knopf 1991). There, as elsewhere along the Rio Grande, the flow regime no longer exhibits flood pulses of historic proportions. The last great pulse resulted in the devastating spring flood of 1941, which may have been responsible for most of the bosque's remaining cottonwoods.

Currently, controlled releases, especially in the downcut reach between Cochiti and Bernalillo, seldom exceed bankfull stage and therefore seldom produce conditions conducive to bosque establishment or maintenance. Meanwhile, the nearly continuous strip of native and introduced trees along the entire middle reach reflects the fact that the river is now stabilized in space by reservoirs, levees, jetty jacks, diversion dams, irrigation systems, roads, and bridges. Thus in historical terms the Middle Rio Grande is a new river with a new bosque. Its flows are about half of what they were six decades ago (Crawford and others 1993) and much of its bosque is hydrologically "disconnected" from the river (Molles and others 1998). As a result, the native bosque is in a state of decline (Howe and Knopf 1991) and has been called an endangered ecosystem (Crawford and others 1996a). How to halt that decline and bring about some degree of partial (functional) restoration is the problem we now address.

Monitoring

There is now widespread recognition of the importance of environmental monitoring (Bricker and Ruggiero 1998). Riparian monitoring is receiving increasing attention (National Research Council 1992) and is emphasized in recommendations of the Middle Rio Grande Ecosystem: Bosque Biological Management Plan (Crawford and others 1993).

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Several agencies, for example the Bureau of Reclamation, have for years monitored shallow groundwater, streamflow rates, and other factors relevant to bosque functioning in the Middle Rio Grande valley.

In contrast, monitoring of a suite of ecosystem variables that both impact and reflect bosque functioning has begun only recently, but has already demonstrated the value of long-term data to support restoration efforts. Monitoring the local bosque's ecology began a decade ago with "Bosque Biology," a University of New Mexico course in which students periodically sample certain elements such as litterfall or arthropod activity. Data collected over the years have proven to be effective indicators of the deteriorating condition of the riparian forest in central Albuquerque (Molles and others 1998). In 1991, lessons learned and ideas developed in the course were applied to a 6-year study (supported through the Fish and Wildlife Service by the Bosque Initiative, in addition to National Science Foundation funds, and performed mainly at the Bosque del Apache National Wildlife Refuge) of the effects of flooding on the bosque's ecology. During that project, the results of year-round monitoring of key biological populations and ecological processes revealed much about the expected magnitude and timing of ecosystem reorganization accompanying experimental flooding (Molles and others 1998). Such insight would not have been possible without adherence to a rigid monitoring protocol.

The Bosque Ecosystem Monitoring Program

Since 1996, the Bosque Ecosystem Monitoring Program, in which biologists at The University of New Mexico and educators from Bosque Prep School work together closely, has incorporated procedures from both of the above studies. Supported initially by the National Science Foundation and now by the Bosque Initiative and Bosque Prep School, the program presently focuses on synchronous monitoring of four identically designed but structurally different sites between northern Albuquerque and Belen. Two of the sites undergo partial flooding in years of high spring flows while the other two, both in Albuquerque, have not been flooded for decades. Data are collected by volunteers (these include students and their teachers at Bosque Prep and in other Albuquerque, Los Lunas and Belen secondary schools, as well as older citizens). Following analysis in The University of New Mexico's Biology Department, the data will become available to bosque managers. Meanwhile, all participants are encouraged to inform their communities of their bosque activities.

Restoration

Preventing the irreversible decline of the Middle Rio Grande bosque is central to the goal of the Middle Rio Grande Ecosystem: Bosque Biological Management Plan. It is also an avowed objective of a variety of federal and state agencies, and of environmental organizations concerned with the condition of the basin's environment. Yet while a number of the plan's management recommendations are being implemented and certain habits are being protected, little is being done to return degraded parts of the bosque to

a state approximating past structure and function. To some extent this is because agencies charged with managing the riverine/riparian ecosystem do not have mandates that contend with ecosystem-level problems. Also, there appears to be no stated consensus among managing agencies as to what "bosque restoration" actually means. Finally, the bosque's relationship with the river brings up the issue of interfering with flow regulation and perhaps water rights, complex matters that are troubling to many.

Still, these difficulties are not insurmountable. Having studied the bosque for many years, we feel that "restoration" is feasible if applied in the context of its limitations. In our view, returning the bosque to some designated historical state makes little sense. Too much change has occurred to the system for that to be a realistic option. We prefer the more flexible concept of "partial restoration" (Crawford and others 1996b), which advocates seasonal soil wetting at carefully selected riparian locations in order to bring about establishment and/or maintenance of native woody vegetation. Such a practice would promote decomposition, mineralization, and nutrient cycling (Ellis and others 1998, Molles and others 1998), thereby reducing the fuel load of accumulated litter (Stuever and others 1997). We contend that a combination of methods, such as simulated flooding, manipulation of flow regime, and alteration of bank structure can be used to this end.

Partial Restoration: Potential Obstacles and Solutions

Flood Pulse Disruption

Because the Middle Rio Grande's late spring flood pulse is more predictable but less extreme than it was before regulation, the opportunity for water to flood overbank is consistently low to the north and high to the south, except during drought years when it is low all over. Assuming continued growth in the basin and concomitant increases in human consumption of Rio Grande water, it is likely that overbank inundation will decline progressively south of Albuquerque. In that case we anticipate two broad solutions to the problem of native bosque establishment and maintenance. One is to mechanically lower the river bank in select places, while the other is to create more sites (mainly point bars) for seedling establishment by increasing the frequency of river meanders and/or braids. Both would effectively return the flood pulse to limited stretches along the river. Examples of both approaches are discussed below.

Exotic Trees

Saltcedar, *Tamarix ramosissima*, is rampant to the south and Russian olive, *Eleagnus angustifolia*, tends to dominate in the north of the Middle Rio Grande riparian forest. In Corrales and other places, Siberian elm, *Ulmus pumila*, is strongly represented in the understory and will likely become the main overstory tree as the old cottonwoods die off in the next century. While these and other exotic trees are difficult to control and have become, for practical purposes, fixtures in the bosque landscape, a degree of containment of these trees is possible, as pointed out in Recommendation

No. 17 of the Bosque Biological Management Plan. Mechanical means (for example bulldozing followed by root plowing) are suggested, and herbicides may be needed as well. As the recommendation points out, if cleared areas are near the river and subject to flooding, they can be converted to new stands of native trees. Recent research by Sher (1998) provides evidence that seedlings of the native cottonwood are competitively superior to those of saltcedar whenever abiotic conditions allow establishment.

Landscape Fragmentation

Recommendation No. 7 of the Bosque Biological Management Plan addresses the problem of bosque fragmentation by multiple forces. Partial restoration of highly fragmented areas some distance from the river but still between the levees may be possible, depending on the kind of disturbance. Further clearing and mechanical lowering of the disturbed site, when combined with soil wetting (using runoff water or other sources) in late spring could be used to recruit native tree seedlings. Pole planting has been successful for small scale restoration and could be useful in many fragmented sites as a supplement to, rather than a replacement for natural cottonwood regeneration.

Bosque Wildfires

Unmanaged bosque wildfires, caused mainly by humans, are on the increase (Stuever and others 1997). Depending on their intensity, they can seriously restrict or inhibit cottonwood regrowth while promoting stump sprouting of exotic trees. For a short time following a fire in late spring, it may be possible to thoroughly wet the soil column by various means (for example flooding from the river or pumped groundwater) to allow pole planting and/or natural cottonwood-willow seedling startup to restore native bosque. Shade provided by mature cottonwoods can greatly reduce saltcedar development (Everitt 1995 and many personal observations), but shade tolerant Russian olive is not so easily constrained.

Beavers and Defoliating Insects

Beavers, *Castor canadensis*, were largely eliminated from the valley in the 19th century, were restocked in the mid-1900s (Crawford and others 1993) and are now common along the Middle Rio Grande, where they live in holes in the bank. Beavers depredate all age classes of cottonwoods (Campbell 1990), but young trees seem especially vulnerable when present. New cottonwoods established by overbank flooding may have to be screened with chicken wire where beavers are active. Alternately, local populations may have to be trapped out and re-located.

Several species of insects account for substantial defoliation of cottonwoods in the bosque (Yong and Crawford 1997, also ongoing research by K. Eichhorst). In particular, the cottonwood leaf beetle, *Chrysomela stricta*, can affect over 60 percent of the leaves produced in the vicinity of Albuquerque, but far less at sites studied to the south. Reasons for this are under current study. Leaf consumption occurs mainly in late spring and early summer, which means that new leaves

form the beetle's diet. Defoliation of seedlings and young trees could be a setback for partial restoration in areas where beetle populations are high.

Partial Restoration: Current Approaches

Hydrologic Manipulation: Alternatives Based on Geomorphology

While there may be fairly broad support for improving the bosque's riverine and terrestrial habitats by "mimicking typical natural hydrographs," and for allowing "fluvial processes to occur within the river channel and the adjacent bosque to the extent possible" (Recommendations 1 and 2, respectively, in the Bosque Biological Management Plan), a consensus has still not been reached on how to achieve these goals.

A consensus based on principles of fluvial geomorphology could be reached, however, because river regulation has resulted in a series of discharge gradients generated by impoundments and/or other diversions that trap sediment moving downstream. The gradients begin with downcutting below such structures, causing what can be termed F or G type channels (Rosgen 1996). As the balance between aggradation and degradation shifts downstream with the addition of sediment from banks and tributaries, the channel tends to take on more of a sinuous or C type configuration. Below that, the increasingly aggraded river becomes wider and more braided, in effect a D type system.

This repeated pattern of flows offers opportunities to apply a variety of hydrologic manipulations to achieve partial bosque restoration. The confined river with its reduced flows provides a hydrologic template that is substantially different from those of the past. Decisions based on cross sectional stream morphology at any location can lead to relatively confident estimates of the discharge required for seasonal overbank flooding at specific sites along a given gradient. The next step, how to manipulate the flow regime in order to make that happen, is more problematic.

Several approaches presently are being considered. One is to move the levees back from the river. Where possible, that would increase the width of the active floodplain. The river then would be able to form new channels, which would create new establishment sites for native woody vegetation. Locations for such a project between Bosque del Apache and the upper end of Elephant Butte Reservoir have been seriously considered by the Corps of Engineers and the Bureau of Reclamation, with some input by environmentalists and non-agency experts, but the matter remains unresolved.

Another option is to increase the degree of braiding of the river bed. As a rule, the river's historic pattern was braided and slightly sinuous (Biella and Chapman 1997). Riparian vegetation would have become established on periodically inundated river bars associated with this pattern, as currently happens in locations characterized by aggraded beds. Mechanically induced braiding could open up additional establishment sites, if desired. The reach below the mouths of the Rio Puerco and the Rio Salado would be a candidate for this approach; it tends to be shallow and wide, and is already braided to some extent.

A third approach is to spatially change the river's flow regime by increasing the number of meanders in given lengths of river. The argument for this is based on the fact that while present meanders were created by heavy flows before the levees were built, regulation has negated future flows of such magnitude. Moreover, since on average the channel contains only about half the water it held in the days before flood control was strongly implemented (Crawford and others 1993), and since river width is a function of river wavelength (Leopold 1994), a given reach can sustain additional sinuosity. That in turn means more point bars for cottonwood-willow establishment.

How these approaches would affect the survival of the endangered silvery minnow, *Hybognathus amarus*, has not been sufficiently examined. If they were to promote overbank flooding during the breeding season, young fish might benefit from nutrient rich water moving slowly through the riparian forest. Other unresolved questions addressing restoration related river manipulation include how and where to do it, who would pay for it, and what political obstacles might impede it. Nevertheless, combinations of manipulation based approaches to partial bosque restoration, when carefully planned and executed, seem reasonable. Flexibility in implementing them would be critical, as would motivation within key agencies. Doing nothing, however, will lead to a collapse of the native bosque.

Albuquerque Overbank Project: an Experiment in Restoration

At this writing the Albuquerque Overbank Project (AOP) is an ongoing experiment to mechanically create a cottonwood-willow establishment site along the Rio Grande within the city limits. The AOP was initiated by a team from the Bureau of Reclamation, The University of New Mexico Biology Department, the City of Albuquerque Open Space, the New Mexico Natural Heritage Program, the State of New Mexico Environment Department, the Middle Rio Grande Conservancy District, the Fish and Wildlife Service, and the Corps of Engineers. It is funded largely by the Bureau of Reclamation, although each of the other entities as well as several volunteers have contributed various forms of support. Rather than dealing directly with the river's hydrology, the AOP is manipulating the river's west bank approximately 5 kilometers south of the Bridge Street Bridge to allow overbank flooding.

The project, diagrammed in figure 1, first involved clearing about 1.6 hectares of dense Russian olive from the downstream half of an alternate river bar. The trees were stockpiled and later removed and chipped. Next, 0.96 hectares of the cleared area by the river were lowered by about 0.6 meters. Roughly 6117 cubic meters of the exposed soil were root plowed and root ripped, then used to cover part of a large sand bar extending downstream from the alternate bar. Undulations throughout the cleared area were created to enhance the chances of cottonwood and willow seedling establishment during the initial phase of post-flood drawdown in late June.

Meanwhile, 18 equally spaced shallow groundwater wells (piezometers) were installed in five equidistant lines leading from the levee to the west, through the existing old bosque, and out to the river. Five wells were placed north of the undisturbed zone as controls and seven more are in the old bosque by the western levee. All wells were surveyed for elevations above sea level; this will enable the team to determine whether site treatment has any influence of groundwater changes. Well monitoring for water depth and chemistry is performed at monthly intervals, or more frequently during peak flooding. Vegetation transects were set up adjacent to the well lines and plant surveys were conducted prior to tree removal. Quadrat sampling along the transects took place prior to tree removal and commenced again following floodwater subsidence. Site patterns of soil salinity were measured twice before overbank flooding began in April.

The AOP's underlying hypothesis is that the treatment will produce a natural plantation of native tree seedlings. Success in the first year of operation will depend on the timing of post-flood drawdown relative to seed arrival. Runoffs in subsequent years will vary and may or may not contribute to what could be the uneven beginning of a new patch of native bosque. The approach is admittedly something of a gamble, but it follows the paradigm of "something is better than nothing."

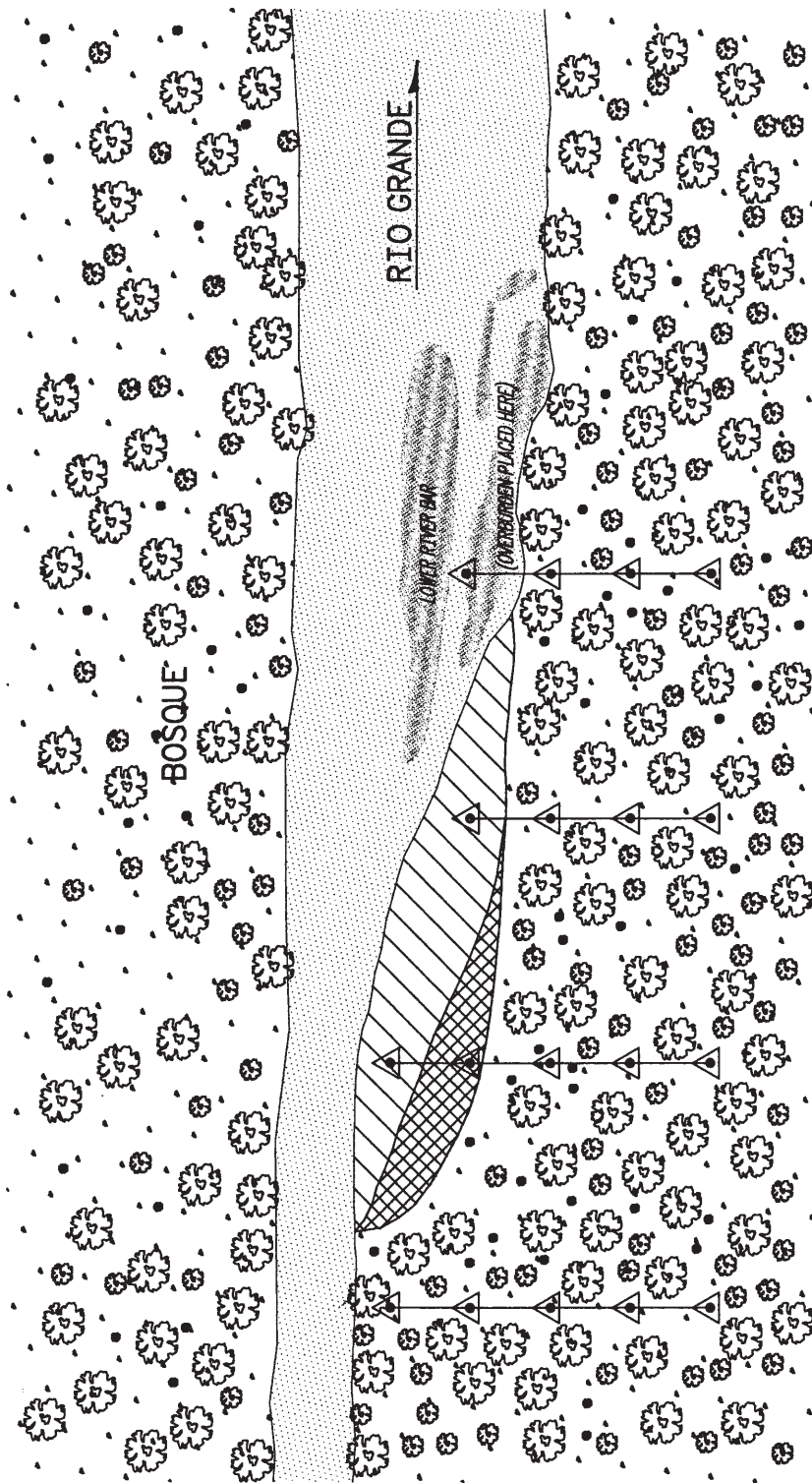
Conclusions

Partial restoration and monitoring of the Middle Rio Grande bosque should be integral to its management. Enough is now known about the ecosystem and its relationship to the river's flow regime and hydrology to efficiently manage for a sustainable riparian forest containing a substantial number of native trees. A flexible program of establishment and maintenance by manipulated overbank flooding will make such management possible, provided resource agencies and environmentally concerned citizen groups work together, acquire funding, and argue successfully for keeping sufficient water in the river for this purpose.

Working together on relatively small restoration projects like the AOP is one way to create a climate of trust and cooperation that can extend to larger, reach length restoration projects. We recommend that such a "bottom up" approach be given increased recognition among agencies responsible for sustainable management of the Middle Rio Grande bosque ecosystem.

Acknowledgments

The authors appreciate the support provided them over the years by the institutions they represent, the Bosque Initiative, and the National Science Foundation. We also thank Bill Zeedyk and Mark Harberg for useful comments on the contents of this paper.



Centerline of
Atrisco Riverside Drain.

PLAN VIEW ALBUQUERQUE OVERBANK PHASE I (NO SCALE)

KEY

Groundwater Monitoring Well

Vegetation Cleared Area

Vegetation Cleared Area (Lowered 0.6± meters)

OCTOBER, 1998

References

- Biella, J.V.; Chapman, R.C. (eds.). 1977. Archaeological investigations in Cochiti Reservoir, New Mexico. Volume 1: a survey of regional variability. Report submitted to National Park Survey, Santa Fe, for U.S. Army Corps of Engineers. Albuquerque, NM.
- Bricker, O.P., Ruggiero, M.A. 1998. Toward a national program for monitoring environmental resources. *Ecological Applications* 8: 326-329.
- Campbell, M.L. 1990. A survey of mammal populations in the Rio Grande Valley State Park. Final report submitted to City of Albuquerque, Open Space Division. Albuquerque, NM.
- Crawford, C.S.; Cully, A.C.; Leutheuser, R.; Sifuentes, M.S.; White, L.H.; Wilber, J.P. 1993. Middle Rio Grande ecosystem: bosque biological management plan. Report submitted to U.S. Fish and Wildlife Service, Albuquerque, NM.
- Crawford, C.S.; Ellis, L.M.; Molles, M.C., Jr. 1996a. The Middle Rio Grande bosque: an endangered ecosystem. *New Mexico Journal of Science* 36: 276-299.
- Crawford, C.S.; Ellis, L.M.; Molles, M.C., Jr.; Valett. 1996b. The potential for implementing partial restoration of the Middle Rio Grande ecosystem. pp. 93-99. In: *Desired future conditions for Southwestern riparian ecosystems: Bringing interests and concerns together*. USDA Forest Service General Technical Report RM-GTR-272, Fort Collins, CO.
- Ellis, L.M.; Crawford, C.S.; Molles, M.C., Jr. 1998. Comparison of litter dynamics in native and exotic vegetation along the Middle Rio Grande of central New Mexico. *Journal of Arid Environments* 38: 283-296.
- Everitt, B.J. 1995. Hydrologic factors in regeneration of Fremont cottonwood along the Fremont River, Utah. *Natural and Anthropogenic Influences in Fluvial Geomorphology*, Geophysical Monograph 89: 197-208.
- Gile, L.H.; Hawley, J.W.; Grossman, R.B. 1981. Soils and geomorphology in the Basin and Range area of southern New Mexico—Guidebook to the Desert Project. New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 222 p.
- Howe, W.H.; Knopf, F.L. 1991. On the imminent decline of the Rio Grande cottonwoods in central New Mexico. *Southwestern Naturalist* 36: 218-224.
- Leopold, L.B. 1994. *A view of the river*. Harvard University Press, Cambridge, MA. 298 p.
- Molles, M.C., Jr.; Dahm, C.N.; Crocker, M.T. 1992. Climatic variability and streams and rivers in semi-arid regions. pp. 197-202. In: Roberts, R.D.; Bothwell, M.L., eds. *Aquatic ecosystems in semi-arid regions: implications for resource management*. N.H.R.I. Symposium Series 7, Environment Canada, Saskatoon.
- Molles, M.L.; Crawford, C.S.; Ellis, L.M.; Valett, H.M.; Dahm, C.N. Managed flooding for riparian ecosystem restoration. *BioScience* (in press).
- National Research Council, Committee on Restoration of Aquatic Environments. 1992. *Restoration of aquatic ecosystems: science, technology and public policy*. National Academy Press, Washington, DC. 552 p.
- Rosgen, D. 1996. Applied river morphology. *Wildland Hydrology*, Pagosa Springs, CO. 343 + xxvi p.
- Sher, A.A. 1998. Seedling ecology of competing riparian tree species: native cottonwood (*Populus deltoides* ssp. *wislizenii*) and introduced saltcedar (*Tamarix ramosissima*). Ph.D. dissertation, The University of New Mexico, Albuquerque, NM.
- Stuever, M.C.; Crawford, C.S.; Molles, M.C., Jr.; White, C.S.; Muldavin, E. 1997. Initial assessment of the role of fire in the Middle Rio Grande bosque. pp. 275-283. In: Greenlee, J.M., ed. *Proceedings of the First Conference on Fire Effects on Rare and Endangered Species and Habitats*. The International Association of Wildland Fire, Coeur d'Alene, ID.
- Yong, T.-Z.; Crawford, C.S. 1997. Ecology of two micro-lepidopteran leaf-rollers in an arid-land riparian forest. *The Southwestern Naturalist* 42: 155-161.

Figure 1—Diagram based on an aerial photograph of the Albuquerque Overbank Project site on the west bank of the Rio Grande approximately 5 kilometers south of the Avenida Caesar Chavez Bridge in Albuquerque, NM. All vegetation was stripped from the barred elliptical zone, and the area between the river and the zone's dividing line was lowered by about two-thirds of a meter in February 1998. Soil removed in the process was deposited on the lower river bar to the right of center. Triangles represent locations of shallow groundwater piezometers along transects also used to study vegetation cover.

Sevilleta Long-Term Ecological Research Program: Measuring Ecosystem Responses to Environmental Change

Robert R. Parmenter

Abstract—The purpose of this paper is to describe the research program of the Sevilleta Long-Term Ecological Research Program (LTER) at the University of New Mexico. Details and data for each of the research topics described can be found in the Sevilleta LTER Internet Homepage (<http://sevilleta.unm.edu>).

The Sevilleta LTER Program is conducted by the University of New Mexico's Department of Biology in close collaboration with the U.S. Fish and Wildlife Service, and is funded by a major grant from the National Science Foundation. The Sevilleta LTER is part of a coordinated network of 21 LTER sites that span North America (including two sites in Antarctica). The Sevilleta LTER Program concentrates its research efforts on the Rio Grande Basin in central New Mexico.

The Sevilleta Long-Term Ecological Research Program (LTER) was initiated in October, 1988, and has focused on a suite of ecological hypotheses concerning climate dynamics and the responses of organisms in a biome transition zone in central New Mexico. The Sevilleta LTER research region straddles several major biomes of the Southwest, and the large geographic scale of the Sevilleta region is important for studies that range from genetics and physiology at the organismal level, to the dynamics of biome transition zones. The region is strongly influenced by the El Niño Southern Oscillation (ENSO), with major fluctuations in precipitation on semi-decadal time scales.

Under the Sevilleta LTER program, mathematical water balance models are providing a unifying synthesis of the LTER core topics and the various levels of organization studied by the participating investigators. The water balance approach takes advantage of continued studies from 1988-1994 (for example, vegetation, climate data, precipitation estimation from lightning, other GIS data, and remotely sensed imagery) and provides a conceptual and quantitative context for a number of new studies that provide a richer and more complete characterization of the Sevilleta region. In addition, LTER scientists will implement a systems model of the CENTURY class in a geographical context, in which the water balance will be driven by the nonequilibrium water model. Thus, the models will provide a synthesis of existing

and future data concerning the core areas of organic matter processing, primary production, and inorganic inputs. The synthesis will be of immediate use in relation to the disturbance and population core topics, including vegetation-environment relations, nutrient dynamics, species distributions and abundances, animal population studies, and population genetics. These field and laboratory studies will provide the necessary biological components that represent the contingencies and feedbacks that are both the responses to, and the constraints on, the dynamics of water.

Site Description

The University of New Mexico's Sevilleta Long-Term Ecological Research Program (LTER) in the central Rio Grande Basin is part of a National Science Foundation network of research sites that examines the responses of ecosystems to environmental changes. The Sevilleta LTER Program is located primarily at the Sevilleta National Wildlife Refuge (Socorro County, NM), but researchers also utilize areas in Cibola National Forest, Bosque del Apache National Wildlife Refuge, El Malpais National Monument, Bandelier National Monument, Los Alamos National Laboratory, Pecos National Historical Park, Petroglyphs National Monument, Kirtland Air Force Base, and the USAF Melrose Range. These varied study sites include a wide range of ecosystem types, including Chihuahuan Desert, Great Plains Grassland, Colorado Plateau Shrub-Steppe, Pinon-Juniper Woodland, Bosque Riparian Forests and Wetlands, Ponderosa Pine Forests, Mixed-Conifer Montane Forests, and Subalpine Forests and Meadows. The dominant theme of the Sevilleta LTER Program is to examine long-term changes in ecosystem attributes (for example, population dynamics of plants and animals, nutrient cycling, hydrology, productivity, species diversity) as a result of both natural and man-made disturbances (for example, global warming, acid rain, grazing, wildfires, droughts, and the "El Niño—Southern Oscillation" (ENSO)). Through these long-term studies, scientists will improve their understanding of the natural dynamics of ecosystems in the heterogeneous landscape of central New Mexico.

Sevilleta LTER: A Regional Research Program

The Sevilleta research region spans the Rio Grande Basin. In the Socorro County area, study site elevations range from 1,350 m at the Rio Grande to 2,195 m in the Los Pinos Mountains in the east, to 2,797 m at Ladone Peak in the northwest, and to 3,450 m in the Magdalena Mountains to

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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the southwest. Other important regional features include the San Agustin Plains to the west, and the Jornada del Muerto ("Journey of Death") valley to the south. The San Agustin Plains is an ancient lakebed, which has had a number of paleoecological studies that have characterized the long-term vegetation changes in the region; it is also the site of the Very Large Array Radiotelescope funded by NSF. The Jornada del Muerto extends southward some 125 km, and is largely uninhabited except for military personnel at the White Sands Missile Range, site of the first atomic bomb test. The Jornada del Muerto area is the northward extension of habitats characteristic of the Jornada LTER.

Variations in elevation, parent material and geomorphic setting have combined to produce a variety of soils and habitats ranging from thin and rocky residual soils to deep alluvium. For example, in the Sevilleta NWR outside of the floodplain, there are 3 orders, 6 suborders, 10 great groups, 17 subgroups, and 38 named series of soils represented. In the floodplain are additional Entisols and Vertisols. The variability attributed to topography, geology, and soils over a number of scales contributes directly to the variety of gradients in the region. There are wide ranges of variation in soil properties such as texture, depth, presence of argillic and calcic horizons, A-horizon organic matter content, temperature and moisture regimes, and salinity.

The imposition of climatic dynamics in combination with diverse microsite characteristics presents numerous, excellent opportunities for research on species and ecosystem dynamics. Climatic dynamics occur over a range of time and space scales and the research region offers an opportunity to examine many of them. There is a rich set of "behaviors" in response to the dynamics of climate. At one end of the spectrum, areas as large as the Sevilleta or Magdalena Mountains can be viewed as a single pixel and will show variations in spectral reflectance from seasonal to annual time-scales and longer. At another point in the spectrum, species are subject to genetic change and demonstrate an evolutionary response to climate dynamics, at both fine and broad scales. In between these examples is a rich diversity of biological and ecological features that can be studied. The current research ranges from studies of genes to landscapes.

Although the dedicated research areas form the core of the site research, there are excellent opportunities to evaluate management influences on species or landscapes. Intensive grazing occurs outside the boundaries of the research areas and fence-line contrasts have been studied frequently. The Rio Grande provides irrigation water, and floodplain agriculture also has been studied. The juxtaposition of reserved and managed areas also allows studies of, for example, species' refuges, dispersal factors, the influence of exotics, and disturbed-land restoration.

LTER in a Biome Transition Zone

Topography, geology, soils, and hydrology, interacting with major air mass dynamics, provide a spatial and temporal template that has resulted in the region being a transition zone for a number of biomes. The region contains communities representative of, and at the intersection of, Great Plains Grassland, Colorado Plateau Shrub-steppe,

Chihuahuan Desert, Interior Chaparral, and Montane Coniferous Forest. The elevational gradient of the Magdalena Mountains provides further transitions for Interior Chaparral, Pinon-Juniper Woodland, Montane Conifer Forest, Subalpine Conifer Forest, and Subalpine Grassland. The Magdalena Mountains represent the northeastern limit of Interior Chaparral and are unique in having both Subalpine Conifer Forest and Interior Chaparral on the same mountain range.

The regional location at the junction of a number of biomes is critical for quantifying (1) gradient relationships with distance, (2) the scale-dependent or independent nature of spatial variability, (3) how steep gradients influence system properties, (4) integrated responses across the region, and (5) biome responses to climate change.

Biodiversity

The size of the area, the heterogeneous topographic and geological features, and the characteristics of a biome transition zone have resulted in a rich diversity of species. At least 104 families, 1,201 species and 208 varieties of plants occur within the study region, and many species are at their distributional limits. For example, 54 plant species terminate their geographic distributions within the Sevilleta NWR. Some of these species represent major life forms and physiologies, such as the C3 perennial grasses (*Oryzopsis*). The terrestrial vertebrate fauna includes 89 species of mammals, 353 birds, 58 reptiles, and 15 amphibians. A substantial proportion of these species have a geographic distribution boundary within the region. Reptiles provide the most dramatic example, as 47 of the 58 species end their distributions in the vicinity of the Sevilleta (33 of these are northern limits of desert species). In addition, a high diversity of ground-dwelling arthropods, with distinctive habitat-specific assemblages, has been documented in recent and ongoing studies.

An important feature of the biodiversity of this region is the number of examples of sympatric swarms of closely related species. This sympatry affords opportunities for studying the evolutionary differentiation of species. For example, six species of mice in the genus *Peromyscus* occur on the Sevilleta (a seventh may also occur), of which five have been found coexisting on a one hectare plot. Four species of *Bouteloua* grasses can be found in the same habitat, and seven species of lizards in the genus *Cnemidophorus* are present. Six of these seven lizard species are found in Sevilleta shrubland habitats, and all seven are present in the shrubland/pinon-juniper transition.

LTER Program as an "Ecological VLA"

At a regional scale, the central New Mexico landscape is composed of a mosaic of biome types, many of which are represented by study sites in the Sevilleta LTER. The study region also straddles the boundary between major seasonal air masses (for example, the "Arctic express" on the Great Plains influences Sevilleta's eastern edge; Great Basin polar air masses extend to Sevilleta's northern edge; the Bermuda High generates summer convective storms over

the mountains, which track northeast across Sevilleta's lowlands). Superimposed on these spatial patterns are the temporal dynamics of the ENSO phenomenon. These climate phenomena are a function of orographic effects of the southern Rocky Mountains and the New Mexico basin-and-range topography.

Given the reasonably large latitudinal, longitudinal and elevational gradients found in the Sevilleta study region, Sevilleta LTER researchers have access to many representative biome "patches" that lie close to the edges of their continental distributions. The LTER capitalizes on this "biome diversity" to scale-up the population, community and ecosystem studies, and address biotic responses to climate change on a regional basis. To accomplish this, we have developed an ecological analog to NSF's Very Large Array Radiotelescope (VLA). The VLA is composed of a series of scattered, individual dish-antennae, that, when monitored simultaneously, reveal high-resolution data on obscure astronomical objects. As a rule, signal resolution increases with greater antennae numbers and spread-diameters.

In line with this approach, the LTER Program established a number of research sites (VLA antennae analogs) in various habitats ranging from Rio Grande riparian forest through grassland, shrub-steppe, desert shrubland, pinon-juniper woodland, mixed-conifer subalpine forest, and subalpine meadow. In combination with the Sevilleta LTER Program, the studies at Bosque del Apache NWR, Cibola National Forest, Kirtland Air Force Base, and four National Monuments are becoming important components of the New Mexico "Ecological VLA." With this network of sites, that spans a two-fold gradient in precipitation amount (VLA spread-diameter analog), we can address problems that require simultaneously-measured, multi-biome data. Such topics include the role of drought or wet cycles on (1) primary production, decomposition and nutrient cycling budgets at a regional scale, (2) species diversities and trophic structures of biotic assemblages across landscapes, and (3) population dynamics and demographics of plants and animals with multi-biome distributions. The benefit of this approach is enhanced greatly by the fact that all these regional research sites are subjected to the same regional climate dynamics; for example, a drought year for one site is a drought year for all. With the ecological VLA approach, the LTER Program can conduct a "natural experiment," examining proportionate or disproportionate responses of biome types under a similar climatic "treatment."

Hypotheses Addressed by the LTER Program

The LTER Program addresses a number of ecological questions, including: 1) How do the El Niño/La Niña climate dynamics influence ecological processes, such as nutrient cycling and energy flows, as well as the population abundances and spatial/temporal distributions of plants and animals; 2) What effects do climate dynamics have on the species compositions and trophic structures of the various biome types; 3) Across the central New Mexico landscape mosaic, are there similar or disproportionate responses among communities in various biome types when subjected to a common, regional climate change (for example, drought);

4) Are patterns of plant and animal demographics, density/abundance, survivorship, and reproduction associated with habitat-specific variables (for example, primary production, precipitation, soil moisture, temperature); 5) How does the heterogeneity of habitat mosaics, in concert with their ecotones, influence floral and faunal distributions, and which species might be poised for habitat invasion/retreat following abrupt or long-term climate changes?

Project Description

The following provides a conceptual description of the Sevilleta research program's present status and future direction, based largely on current trends and national funding priorities in ecological research. Following this section is a more detailed projection of the long-term future of the Sevilleta LTER Program.

The primary values of the research region include: (1) the dedicated research areas occupying a large area (150,000 ha), (2) the location at transitions spanning a number of biomes, and (3) the high biological and environmental diversity. The transitions can express themselves in a number of ways, as various gradients of soils, geology, and topography change through space and time. Climate change will also express itself over a range of time and space scales and the ecological transitions of the Sevilleta region represent an opportunity to examine many of them. We anticipate that the area will demonstrate a wide range of "behaviors" in response to the dynamics of climate. For example, the 1950's drought caused marked vegetation boundary movement in much of the region. The 1988-89 La Niña event produced a strong winter drought that prevented spring production of C3 grasses. Other wet years in the early 1990's caused increased production and expansion of C3 perennial grasses (*Oryzopsis*). The area is expected to provide a rich set of ecological "tools" capable of quantifying the range of responses to environmental dynamics.

The high biodiversity is related to the large area, heterogeneous habitats and the transitional area for so many biomes. This offers excellent possibilities to understand the factors that contribute to the high diversity, including the high degree of sympatry for closely related species. Population studies are focusing on the interaction between climate change and evolutionary change. Climate change may both stretch the limits of response and change the process of evolution through climate-induced changes in population structure. The effects of a dynamic and heterogeneous environment are expected to be magnified for species at the margins of their ranges. Such species, near the limits of physiological tolerance, are most likely to be affected by short time scale changes, and their population dynamics may reflect the rapid environmental changes typical of this region.

Disturbance patterns and frequencies are important forcing functions for the ecology of the area. "Disturbance" is viewed and studied across many scales that range from antelope hoof-marks in the soil crust between plants, to individual plant mortality (gap dynamics), to mammal mound activity, to frequency and intensity of flooding/scouring in ephemeral streams, to the grassland and forest fires that are increasing in frequency in the protected areas, and to decadal patterns of climate dynamics.

Landscape dynamics also receive significant attention. The hundreds of square kilometers surrounding the Sevilleta Field Station provide a natural laboratory for studying the interplay between temporal environmental variation and the spatial patterning of habitat. Viewed from afar, the extensive landscape exhibits repeating patterns of low-elevation grassy plains punctuated by ascending topography that may be viewed as a superstructure upon which environmental gradients are arrayed. As precipitation and temperature vary temporally, we expect to see spatially correlated shifts in the distributions of habitats, and consequently species distributions may be envisioned as ever expanding and contracting mosaics constrained by the shifting habitats. An interesting analogy between the landscape dynamics and the annealing of alloys provides a theoretical framework for the envisioned fluctuations. Annealing is the process of repeated heating and cooling of mixtures. Heating excites the component molecular species to seek new configurations that result in minimized free energy levels upon cooling. Variation in annual precipitation constitutes an "excitation" of the system, thereby allowing the entire collection of species to seek new "free energy levels" which may be characterized by such measures as genetic similarity, species richness (per area), primary production, or by multivariate vectors of community composition. The free energy achieved depends on the organismal, demographic, community, and ecosystem level interactions of the populations involved.

Restoration biology also is an area of intense interest in the region. The grassland and desert shrub areas of most of New Mexico were heavily grazed for centuries. The research areas allow experiments and studies of natural succession and recovery. Species reintroductions also are being planned, such as the native Desert Bighorn Sheep in the Sierra Ladrones and pronghorn antelope on the Sevilleta NWR west of the Rio Grande. The riparian cottonwood forest along the Rio Grande also has been greatly altered by harvesting, river control from impoundments, and invasion by exotics. UNM and FWS ecologists have initiated a new research program at Bosque del Apache NWR that examines aspects of cottonwood forest restoration, focusing particularly on flood manipulations of the Rio Grande and the effects on riparian forest ecosystem processes.

Summary of "Core" Program Studies

The Sevilleta LTER Program is an integral part of the regional research effort, and has already proven to be a tremendous asset to both resident and visiting research scientists. The "long-term" nature of the LTER funding schedule (6-yr intervals) contributes a large degree of continuity and stability to the region's research program, ensuring consistent collections of important "core" data sets. The following sections summarize the various ecological research programs that continually accumulate these "core" data sets, all of which are accessible to any interested scientist. The existence of these ongoing projects greatly enhances the data bases available to scientists during all phases of project implementation, from hypothesis development and experimental design through data analysis and interpretation. The LTER "core" projects take advantage of the region's large size and valuable characteristics as a

biome transition zone. The approaches are designed to emphasize a variety of scales and levels, including landscapes, phenotypic plasticity, and evolution. Numerous other ongoing studies in geology, anthropology, hydrology and geomorphology will not be discussed because of space limitations.

Meteorological Studies

The Sevilleta NWR has been instrumented with 7 fully-equipped meteorological stations and data-loggers, over 50 rain gauges, and an additional 20 collectors for precipitation chemical analysis. The Langmuir Laboratory is also equipped with meteorological stations. Historical weather records (100+ yr) for the region are available from the Socorro, NM, weather station. The LTER also acquires lightning strike data (frequencies and locations) for the entire central New Mexico region. All weather data are archived in the Sevilleta Information Management System (SIMS), and are available on request.

Vegetation Assemblage Studies

The principal, large-scale environmental gradients are related to the north-south and east-west characteristics of meteorologic dynamics and topography. Major transects 3 km wide, 30 to 50 km long are designed to traverse the transitions between biome types as well as maximize or minimize environmental gradients (for example, temperature and precipitation) and elevation. Transects of this scale allow remote sensing analyses from aircraft and satellite to be coordinated with balloon photography and ground truthing to identify gradients in spectral reflectance, species distributions, and substrates. Within the transects, 1 km² plots concentrate traditional plant (as well as animal) measurements and permanent photography quadrats.

Watershed Studies

The justifications for including a watershed approach within the region are: (1) water courses amplify variation in precipitation, especially in arid and semiarid regions where there is a nonlinear relationship between variation in precipitation and variation in runoff. Hence, biological responses (demographic, functional, etc.) to changes in mean climate will be magnified along ephemeral watercourses; (2) drainage networks have a natural, hierarchical organization and scale by both size and dynamical behavior, with the smallest watersheds flowing at high frequency and low magnitude and large watersheds at low frequency and high magnitude (Yair 1983, Yair and Shachak 1982); (3) watershed studies have, as a central focus, movement of water across the landscape (the focal constraint in the region's ecology), and represent especially steep, spatially predictable, gradients in water availability; and (4) watershed-based analyses allow comparative studies with other research environments. The watershed studies are based on a conceptual view of watershed processes developed in the Negev Desert. The focus is on biotic responses to the hydrologic redistribution of water as a consequence of interaction between scale, climate, local geology, and microtopography.

These interactions result in spatially predictable patterns of average runoff intensity and frequency. During the last ten years, eight ephemeral stream sites nested within the Rio Salado drainage have been studied with watershed areas spanning several orders of magnitude (4 at about 22 ha, 2 at 240 ha, 1 at 3,000 ha, 1 at 300,000 ha). The hydrologic data of U.S.G.S. for the Rio Puerco (1 million ha) and the Rio Grande (5.5 million ha) provide long-term, broad scale results. Recent studies of El Niño/La Niña effects in the region also identify temporal predictability at certain scales. The watershed studies (1) form a model for studies of other constraints which change across scales in other landscapes, and (2) form an empirical basis in attempts to link ecological studies to regional and global biogeospheric studies.

Plant and Animal Population Studies

For plant population studies, the ideas focus on the interaction between climatic change and evolutionary change. Climate change may both stretch the limits of response and change the process of evolution through climate-induced changes in population structure. For long-lived species, it is crucial to understand the limits of phenotypic response. For shorter lived species, genetic change is possible. The effects of short term climatic change on the evolutionary process is being studied by investigating the effects of La Niña and El Niño conditions on gene flow and reproduction in current populations.

Plant productivity responses to environmental dynamics may change beyond simple responses to climate due to enhanced susceptibility to herbivores. Monitoring specific interactions between a plant species and its herbivores show at what levels plants react initially to climate change. Genetic variation of spatially separated populations and changes in response to changing environment as well as altered herbivore interactions are hypothesized to control landscape patterns of species.

For animal populations, movement of individuals is being quantified, as well as dynamics of populations, abundance and distribution of species, and trophic and taxonomic composition of assemblages of mammals (rodents, rabbits, coyotes), birds, and surface-active arthropods. Patterns and rates of genetic change (in isozymes and mitochondrial DNA clones) are monitored in rodents. These measurements are made over a sufficient range of spatial and temporal scales: (1) to document the response to heterogeneity across the entire region; and (2) to assess the detailed response of individuals and local populations to both natural environmental change and any experimental manipulations. Specimens are sorted and recorded using the Museum of Southwestern Biology (MSB) computerized information retrieval system.

Fertilization Studies

The abundance of plants from many different biomes suggests intriguing questions of nutrient limitation. Ecosystem nutrient limitation has been noted in many studies while others clearly indicate that each species responds individually to resource availability in relation to its requirements. The ability to predict strong El Niño or La Niña events offers additional capabilities to study nutrient

limitation. During wet springs associated with El Niños, cool season plants are expected to be limited by nutrients rather than moisture. The warm season grasses also would be nutrient limited during an El Niño year because of nutrient immobilization by spring growth of cool season grasses. In La Niña years both cool and warm season grasses should be more water limited than nutrient limited. Fertilization experiments on Sevilleta grasslands have been initiated to evaluate these hypotheses.

Wildfire Studies

Natural fires have become more common on the grassland areas of the protected research areas (no cattle grazing). The studies of these natural fires shows that the influence of fire is very species specific because perennial grasses with large, belowground root systems (for example, Blue Grama of the Great Plains flora) survive while Chihuahuan Desert species (for example, Black Grama, desert shrubs) are depleted. Thus, in the tension zone between Chihuahuan and other biomes, fire may be a primary agent in controlling species movement due to climate dynamics. In areas where the desert species have been established for a longer period (i.e., more like desert habitat than transition habitat), the grass component has been greatly reduced and fires are rare or nonexistent. The natural fires allow studies of species and the effects on subsequent ecosystem processes. Factorial experiments have been conducted that relate burning and herbivore (large ungulates) activity to plant and animal community composition and ecosystem processes.

Future Research Potential

Based on current research activity in the Sevilleta region, as well as on the research activity projections considered internally and with potential visiting researchers, several major avenues of future research are anticipated. First are ecosystem- and community-level studies addressing the effects of climate change on biotic systems. These will include both seasonal, annual, decadal (and longer time scales) fluctuations and trends in climatic variables, and the eventual responses in ecosystem structure and function among the various biomes represented in the Sevilleta region.

Second, a dramatic increase in population- and organism-level studies can be expected in response to the increasing concern about world-wide patterns of declining biodiversity. Included in this category of research are studies concerning the genetic variability of existing plant and animal species, and the historical implications. As mentioned above, the Sevilleta is an extremely species-rich region, and many species therein occur near the boundaries of their range distributions. As such, they are subjected to environmental conditions that, for them, may be extreme. In some cases, for example, a species of desert millipede, the region contains only isolated, relict populations that are widespread elsewhere. Comparisons of genetic similarity among these and other species populations that, over time, have colonized marginal habitats in the Rio Grande Basin, will be of prime importance in LTER studies.

Third, an increase in the number of studies concerning the relationship between ecosystem restoration and biodiversity

is anticipated. The Rio Grande Basin as a whole has been overexploited in a number of ways, particularly in the past century. Currently, however, much discussion and some research has centered on restoration of the region's semi-arid grasslands and on the marshes and gallery forests associated with the Rio Grande itself. The Sevilleta NWR contains extensive grasslands that have been free of livestock grazing for nearly two decades. Studies of the effects of livestock removal on the diversity of grassland biotas are underway and more are planned. The Rio Grande Valley has lost most of the marshland that made it one of North America's most important migration routes for birds. The introduction of salt cedar and Russian olive trees in this century has greatly compounded that loss in terms of habitat alteration. Significant strides to correct these alterations have been made by the Fish and Wildlife Service at the Bosque del Apache NWR, where federal and UNM biologists have begun collaborative studies on restoration of the original wetlands.

Fourth, a number of current and planned research projects on the Sevilleta concern the research and development of new technologies for use in ecological studies, and the application of current technologies to field research. For example, the development of field FTIR (Fourier-Transform Infra-Red) technology to measure trace atmospheric gas production over km² areas of natural ecosystems has been and continues to be an active program on the Sevilleta. In addition, Sevilleta researchers are developing a 3-dimensional, advanced image processing system that will calculate plant biomass from stereoscopic photographs of permanent study plots. An example of integration of existing technologies is the collaborative effort between UNM and NMIMT to correlate lightning activity during thunderstorms with realized precipitation. A 20 km² grid of 25 tipping-bucket rain gauges, each gauge instrumented with a data logger, provides rainfall timing and distribution data that are integrated with temporal and spatial lightning data collected simultaneously by Langmuir's Lightning Detection System. As future technology is made available for scientific use, Sevilleta LTER researchers will continue to develop practical applications of technology for ecological research.

Educational Activities: REU and UMEB Programs

The Sevilleta Research Experiences for Undergraduates Program and the Undergraduate Mentorships in Environmental Biology Program continues to operate in collaboration with the Sevilleta LTER. As in prior years, the goals of these programs are to (1) instruct undergraduates in the principles of scientific research, (2) expose the students to a wide variety of ecological research techniques and career opportunities, (3) facilitate individual student research projects, and (4) encourage students to continue their scientific education in upper-division courses and graduate school. To accomplish these goals, the programs include (1) orientation meetings and a seminar series devoted to the variety of scientific opportunities in ecological research at the Sevilleta, (2) faculty-student one-on-one instruction of hypothesis development and research protocols in ongoing Sevilleta LTER projects, (3) field and laboratory experiences in sampling and data collection, (4) implementation of

individual student research projects, carried out under the guidance of student-selected faculty members, (5) a Sevilleta REU Symposium for project presentations by the students, (6) attendance at scientific meetings, and (7) preparation and submission of project manuscripts to scientific journals. These activities integrate all theoretical and technical aspects of the LTER and promote a holistic approach to large-scale ecological studies.

Applications of Sevilleta LTER Databases

The following is a brief description of how Sevilleta LTER results to date have been incorporated by agencies, resource planners, etc., into their management plans or processes.

(1) Public Health — Hantavirus: Sevilleta LTER data have been used by Public Health officials and the Federal Centers for Disease Control and Prevention in assessing the causes and circumstances of the 1993 Hantavirus epidemic in the Southwest. In addition, the CDC continues to collaborate with the Sevilleta LTER, via a separate grant to Co-P.I. Terry Yates, to monitor rodent populations and hantavirus prevalence in wild rodents.

(2) Land Management — Fire ecology: LTER studies of ecological responses to fires in Sevilleta's grasslands have yielded data on plant and animal survivorship and recolonization. These data have convinced the Fish and Wildlife Service to discontinue fire suppression in grassland/shrubland areas of the refuge, and allow lightning-caused fires to burn in a natural fashion. FWS will continue to stop fires in woodlands, but they have recognized the value of fires in grasslands in maintaining open grass habitats and curtail shrub invasions and desertification.

(3) River Management — Flooding on the Rio Grande: With additional funding from FWS, UNM Biologists Cliff Crawford and Manuel Molles are investigating the role of artificial flooding in restoration efforts along the Rio Grande. Floods are essential for reseeding cottonwood forests, and influence various ecosystem processes, such as wood and leaf litter decomposition and soil nutrient cycling. Sevilleta LTER data from the LTER site at Bosque del Apache NWR are being used in this project. Results from the study are being incorporated into the river management plan by the various state and Federal agencies responsible for flow regulation of the Rio Grande.

(4) Water Use Policies — El Niño: LTER researchers have provided to the public and the state and local governments a continuous stream of data on the ecological and hydrological effects of the El Niño - Southern Oscillation (ENSO) dynamic in New Mexico. Considerable press and TV news coverage has raised the public awareness of the ENSO phenomenon, and some planning decisions by the State Water Engineer have been based on ENSO predictions (for example, reduction of irrigation water allowances in 1992 after sufficient water was predicted during the El Niño of that year; extra water was allowed to flow to Texas, to pay off part of New Mexico's water debt).

(5) Rangeland Resource Use — Grazing Issues: LTER studies of livestock grazing on private rangeland adjacent to the Sevilleta NWR have been incorporated into the ongoing debate on use of western Federal lands for grazing. Policies on grazing are currently being considered at Federal and State levels.

Influence of Mycorrhizal Source and Seeding Methods on Native Grass Species Grown in Soils from a Disturbed Site

Todd R. Caplan
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Abstract—Mycorrhizal fungi are crucial elements in native plant communities and restoring these fungi to disturbed sites is known to improve revegetation success. We tested the seedball method of plant dispersal for restoration of plants and mycorrhizal fungi to disturbed ecosystems. We tested the seedball method with a native mycorrhizal fungi inoculum, and a commercial inoculum. We found that the native culture and commercial inoculum were not viable sources of mycorrhizae.

The role of mycorrhizal fungi in ecological restoration has been a topic of great interest to scientists for more than two decades. Mycorrhizal fungi are known to aid plants in acquiring water and nutrients, most notably phosphorus, in exchange for carbohydrates and sugars provided by the plants through photosynthesis. This relationship is thought to benefit not only individual plants, but entire plant communities (Allen and others 1995; Francis & Read 1994; Francis & Read 1995). However, human activities which cause severe soil disturbance may result in the reduction or complete loss of mycorrhizal propagules from the soil (Allen & Allen 1980; Allen and others 1987; Reeves and others 1979). Several ecologists, including Allen and others (1987) and Reeves and others (1979), believe that successful plant community restoration may ultimately depend upon the re-establishment of this mycorrhizal relationship.

Unfortunately, few methods have been developed for re-introducing mycorrhizal fungi to disturbed soils. The method most typically employed involves inoculating nursery plants with the fungi prior to field planting. While this method has been shown highly successful in forest/shrub land restoration, planting nursery raised plants is expensive, labor intensive and impractical when attempting restoration of grass and forb dominated plant communities (i.e. tundra and grassland). Practical and affordable methods for restoring mycorrhizal plants to disturbed grassland and tundra environments are greatly lacking. In fact, we

know of no published research investigating such methods. However, a method developed by an organic farmer in Japan may provide an excellent tool for restoring herbaceous mycorrhizal plants to disturbed landscapes.

For over fifty years, Masanobu Fukuoka, a Japanese scientist and farmer, has been practicing a method of sustainable organic farming which centers around the planting of seedballs (Bones 1996). Seedballs are simply a mixture of clay, soil humus, and plant seed rolled into small balls the size of deer droppings. Fukuoka combines seed from over 100 species of vegetables and fruits into these balls and scatters them by hand throughout his field. The clay provides a barrier against seed herbivory, re-dispersal of seeds by wind, and exposure to harsh environmental conditions. The soil humus provides an immediate source of mineral nutrients and soil micro-organisms. The purpose of including seed from a high number of plant species is to provide a soil seed bank from which any number of seeds may germinate in a given year depending upon current climatic conditions. Fukuoka's crop productivity has consistently rivaled or surpassed those of neighboring farmers employing more labor intensive and costly practices that utilize more traditional farming methods (fertilizer inputs, tilling, flood irrigation, etc.).

While seedballs have primarily been used for growing food crops, the concept is intriguing for use in native plant community restoration. By substituting native grass and forb seeds for agricultural crop seeds, land managers restoring disturbed areas with seedballs may benefit from increased ground cover and native plant diversity compared to seeding using traditional broadcasting methods. Seedballs may also be an effective means of restoring a much needed seed bank to severely disturbed soils. Furthermore, by incorporating mycorrhizal fungi into the seedball mixture, emerging seedlings will benefit from the increased water and nutrient uptake in disturbed soils supplied by the mycorrhizal fungi. These methods for restoring mycorrhizal grasses and forbs, however, have never been experimentally tested.

It is important to note that limited options for re-establishing mycorrhizal grasses and forbs to disturbed ecosystems is not the only problem facing restoration ecologists. A difference of opinion has recently surfaced over the best methods for developing mycorrhizal inoculum for restoration plants. The few companies known to us who engage in the production of mycorrhizal inoculum, utilize a method which involves promoting reproduction of arbuscular mycorrhizal (AM) fungi collected from a single

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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source. One to a few fungal species are carefully selected and progeny from this "mother" culture are used to inoculate plants for different restoration sites. Inoculum developed from AM collected in the Pacific Northwest, therefore, may be used to inoculate plants for a restoration site in New Mexico. The fungal species bred for these bulk cultures are generally selected because they are aggressive root colonizers, are relatively easy to grow and are present in soils world-wide.

Bulk inoculum containing one to a few ubiquitous fungal species may not be the best approach to inoculating restoration plants. One argument is based upon the fact that different mycorrhizal fungi may be active on the same host plant at different times in the year (Allen and others 1995; Sanders & Fitter 1992; Siguenza and others 1996). Inoculum containing only one or two species, therefore, may provide little or no functional benefit to its host during certain times of the growing season or under variable environmental conditions. Another argument is that even though a given AM fungi species is ubiquitous, different genotypes probably exist which influence plant function differently depending on the biome from where it was collected. For example, Allen and others (1995) found that similar morphotypes of AM fungi collected from different sites confer different physiological benefits to the same plant species. These arguments have led us to ask the question: Will plants used in ecological restoration efforts derive greater benefit (increased growth and survival) from local AM fungi inoculum compared to non-local, commercial inoculum containing one or a few AM fungi species?

We addressed this question in a controlled greenhouse experiment while simultaneously investigating the seedball seeding method for seed germination and inoculation. We believe these methods, once perfected, have great promise for large scale application.

Methods

Greenhouse

Soils used for the greenhouse experiment were collected from several locations within a 200 acre Saltcedar (*Tamarix chinensis*) / Russian olive (*Elaeagnus angustifolia*) stand on Santa Ana Pueblo in Bernalillo, NM. The soil was collected

from 27 random sites from an area of known low salinity. We sieved the soil through 2 mm sieves to remove organic debris. We sterilized the soil by microwaving it for 150 seconds per kilogram of soil. The soil reached mean temperatures of 97 °C (s.d. 10.7). One untreated, and one sterilized representative sample were sent to the SWAT Laboratory at New Mexico State University, Agronomy and Horticulture Department and analyzed for macro and micro nutrients, organic matter, pH, texture, and electro-conductivity (table 1).

The soils were placed in flat cedar boxes (15" x 20" x 12") in the Rocky Mountain Experiment Station greenhouse and seeded with three locally native grassland species according to the following treatments: 1) seedballs with cultured native AM fungi inoculum; 2) seedballs with commercial AM fungi inoculum; 3) seedballs with sterilized inoculum (control); and 4) broadcast seeding. We planted each box on July 30, 1997. The species of grass utilized were *Sporobolus cryptandrus*, *Hilaria jamesii*, and *Bouteloua gracilis*. Each treatment was replicated five times, yielding twenty boxes (samples) total.

We made seedballs by combining specific quantities of clay, soil humus, plant seed and water, then rolling them into small balls the size of elk droppings. These quantities follow methods outlined by Harris (1996). In addition, mycorrhizal fungi from two sources were incorporated into the seedball mix. Seedballs in treatment 1 had native AM fungi inoculum cultured in Santa Ana greenhouse and seedballs in treatment 2 had commercial AM fungi inoculum purchased from a bulk producer and distributor. Methods for culturing indigenous AM fungi followed Menge (1984) and Morton (1996).

Bioassays

Plant contents from each sample were harvested when the majority of plants approached senescence on October 19, 1997. Upon harvest, individual plants were separated and species composites were formed. We collected 0.3 g of root segments from these composites to determine percent mycorrhizal root infection. In addition, oven dry weight measures of root biomass and shoot biomass were measured for each composite sample. Finally, portions of the dried shoots from each composite sample were ground and sent to the SWAT laboratory for tissue phosphorus and nitrogen analysis.

Table 1—Analyses of untreated, and sterilized soil samples for pH, electro-conductivity, nutrient content, and texture.

Test parameter	Untreated	Sterilized
pH	7.75	7.48
Electro-conductivity	2.20 mmhos/cm	2.55 mmhos/cm
Magnesium	2.40 meq/L	3.25 meq/L
Calcium	6.31 meq/L	8.44 meq/L
Sodium	12.05 meq/L	13.10 meq/L
Sodium Absorbion ratio	5.77	5.42
Calculated Exchangeable NA pct-ESP	6.8	6.3
Organic material - pct	1.29	1.61
NO3-N 1:5 (soil:water) extract	1.1 ppm	1.1 ppm
Phosphorus (NaHCO3 extracted)	17.6 ppm	8.1 ppm
K 1:5 (soil:water extract)	64 ppm	63 ppm
Texture of soil by feel	sand	sand

Table 2—Means and standard errors of percent AM fungi colonization, root biomass, shoot biomass, tissue N, tissue P for each of the treatments; control (sterilized inoculum), cultured native inoculum (native), commercial inoculum (commercial), and broadcast seeding. F-probability statistic shown for each variable. Letters reflect significant groupings by one way ANOVA analysis.

Treatment	Per. colonized	Root biomass	Shoot biomass
Control	0.40 (s.e. 0.30)	40.89 (s.e. 5.20)	35.8 (s.e. 3.6)
Native	0.99 (s.e. 0.38)	46.65 (s.e. 5.01)	43.9 (s.e. 4.2)
Commercial	4.51 (s.e. 2.14)	54.14 (s.e. 5.06)	38.4 (s.e. 2.7)
Broadcast	1.50 (s.e. 0.58)	56.89 (s.e. 2.62)	36.5 (s.e. 1.6)
F-prob	0.055	0.097	0.30

Treatment	Tissue N	Tissue P
Control	0.61 (s.e. 0.03) C	0.08 (s.e. 0.01)
Native	1.04 (s.e. 0.05) A	0.09 (s.e. 0.01)
Commercial	0.82 (s.e. 0.08) B	0.09 (s.e. 0.01)
Broadcast	0.58 (s.e. 0.04) C	0.09 (s.e. 0.01)
F-prob	0.0000	0.86

The 0.3 g root segments used for percent root infection were immediately placed in tissue cassettes and immersed in 50 percent ethanol solution. We cleared the roots prior to staining by alternating them between a 10 percent potassium hydroxide solution and a 1 percent hydrogen peroxide solution for approximately 50 hours or until each sample was observed to be cleared. The samples soaked in each solution for at least 1 hour and up to 10 hours before changing to the other solution. After clearing, we stained the roots in a 5 percent trypan blue solution in lactoglycerin. Fungal colonization of the roots was evaluated using the gridline intersection method described in Brundrett and others (1994).

Samples of the commercial inoculum, cultured inoculum, and microwaved soil were sent to Joe Morton's lab at West Virginia University in Morgantown, WV for an infectivity assay. The assay determined the presence, quantity and identity of mycorrhizal spores by utilizing a mean infection percentage assay (Morton, 1996).

Results

Treatment Effects

A one-way ANOVA test was performed for analysis of treatment effects on each of the following variables; percent of root length colonized by arbuscular-mycorrhizal (AM) fungi, root biomass, shoot biomass, tissue nitrogen, and tissue phosphorus. The treatment effects were analyzed across all species (table 2).

The commercial inoculum treatment resulted in relatively high percent AM colonization, but there were no significant treatment effects. The values obtained for percent AM colonization were so low as to be negligible in all treatments.

No significant treatment effects were recorded for root or shoot biomass.

There were significant treatment effects for the plant tissue nitrogen. The highest accumulation occurred in the native inoculum treatment followed by the commercial inoculum treatment. The control treatment and the broadcast

treatment were not significantly different. The tissue phosphorus values did not differ significantly between the treatments.

Species Effects

A T-Test was used to test for species effect since the *H. jamesii* plants were inadvertently removed from the boxes during the experiment. Plant tissue phosphorus was significantly greater in the *S. crytandrus* than in the *B. gracilis*, but there were no significant species effects for plant tissue nitrogen (table 3). Other analyses were not performed due to missing data. All tests were conducted on Statistical Software for the Social Sciences (SPSS 5.0).

Infectivity

The infectivity assays for the cultured inoculum, the commercial inoculum and the microwaved soil all had the same result: there were no viable spores in any of the samples.

Discussion

In this experiment we attempted to test two new techniques for restoring mycorrhizal plants to disturbed areas, the seedball method of dispersal, and utilizing either native

Table 3—Means and standard errors for tissue N and tissue P for two of the grass species, *Bouteloua gracilis* and *Sporobolus crytandrus*. F- probability statistic is shown for each variable. Letters reflect significant groupings by T-Test.

Species	Tissue N	Tissue P
<i>Bouteloua gracilis</i>	0.73 (s.e. 0.06)	0.08 (s.e. 0.00) B
<i>Sporobolus crytandrus</i>	0.74 (s.e. 0.052)	0.10 (s.e. 0.00) A
F-prob	0.91	0.002

or commercial AM fungi inoculum. Both of these techniques have great potential, and further work may address the complications we encountered in this experiment.

Seedball Method

We made seedballs with a commercially available red pottery clay substrate. None of the seedballs dissolved completely during watering in the greenhouse though the boxes were thoroughly soaked daily. We attribute this to adding too much clay to the seedball mixture. The plants that grew in the seedball treatments sprouted directly out of the seedballs but only the seeds on the periphery of the seedballs germinated. Although there was no significant difference in biomass between treatments, we observed that grasses from the seedball treatments were substantially larger in size than the broadcast treatments. The observed size difference between plants in seedball and broadcast treatments is attributed to fewer numbers of individuals in the seedball treatments and greater competition for nutrients in the crowded broadcast treatment samples.

AM Fungi Inoculum

The question of using an AM fungi inoculum in the seedball is complicated. Although we found significant treatment effects in the tissue nitrogen analysis, the infectivity assay results showed that our inoculums, both cultured and commercial, had no viable spores.

AM fungi propagates by two methods, spores and hyphae. The spores are the sexually produced propagules. Hyphae are the “body” of the fungi and penetrate the root cortex cells of the host plant and extend out into the rhizosphere. Often hyphae will extend from one host plant’s roots to the roots of another neighboring plant. By this “vegetative” means, the hyphae of a single fungi are spread throughout a community.

We attempted to infect our experimental grasses with AM fungi spores harvested from the native culture we generated in the Santa Ana Greenhouse, and from AM fungi spores we ordered from a commercial supplier. Both of these sources were later found to be unreliable for viable spores. We checked the roots of the native culture host plants for percent of root length colonized by AM fungi prior to the experiment and found them to be highly mycorrhizal (mean 45.7 percent). So why were there no viable spores in the native inoculum? It has been hypothesized that sporulation will not occur for an individual AM fungi until root colonization reaches values of 30- 40 percent of root length (Morton 1998, personal comm.). Southwestern AM-fungi has high levels of diversity, and although the root length colonized in the native culture host plants appeared to be high enough to have sporulation, there were no spores. This phenomenon may be explained by the presence of more than one species of AM fungi colonizing the roots although it is not possible to identify AM species without spores. Multiple species occupying the same host plant has been observed in other studies (Allen and others 1995; Sanders & Fitter 1992; Siguenza and others 1996). In our culture host plants, one species of AM fungi may be colonizing 20 percent of the root length, another may be colonizing 10 percent, while a third species

may occupy the remaining 15 percent. It is nearly impossible to distinguish between species of AM fungi in this type of assessment. So what we thought was extensive colonization by one species of AM fungi may have been 2 to 3 different species colonizing the same plant. Given this hypothesis, AM fungi in the Southwest would rely more on hyphal propagation than sporulation due to the high diversity of AM fungi available for colonization. Future attempts to inoculate restoration plants using seedballs may require relying upon AM hyphae by mixing segments of the roots of the native culture host plants into the seedballs, rather than relying upon spore production. The hyphae within these root segments, therefore, will then colonize the roots of target plants “vegetatively.”

We returned the commercial inoculum for a refund. Repeated analyses of various commercial inoculums have shown similar results. Commercial sources of mycorrhizal inoculum should be tested for viable propagules prior to experimental or practical application.

The differences we observed in our experimental treatments between tissue phosphorus were probably not due to mycorrhizal effects, evidenced by the extremely low values of root colonization. They may be attributed to competitive effects related to the clumped dispersal of the plants emerging from the seedballs.

We still believe that seedballs can be excellent method of seed dispersal for restoration projects. Incorporating root segments of the native culture host plants containing hyphae into the seedballs may accomplish both goals of restoring not only the seeds of native plants, but the native AM fungi that have been removed from a disturbed area.

Acknowledgments

The researchers thank the Rocky Mountain Experiment Station for funding and use of greenhouse and laboratory space to conduct this research. We also thank the U.S. Fish & Wildlife Service for providing additional funding for supplies and some laboratory analysis. Special thanks to Randi Paris and Gary Desselle for their assistance with this project.

References

- Allen, E.B. and M.F. Allen. 1980. Natural re-establishment of vesicular-arbuscular mycorrhizae following strip-mine reclamation in Wyoming. *Journal of Applied Ecology*, v.17:139-147.
- Allen, E.B., Allen, M.F., Helm, D.J., Trappe, J.M., Molina, R. and E. Rincon. 1995. Patterns and regulation of mycorrhizal plant and fungal diversity. *Plant and Soil*, v.170(1):47-62.
- Allen, E.B., Chambers, J.C., Connor, K.F., Allen, M.F., and R.W. Brown. 1987. Natural re-establishment of mycorrhizae in disturbed alpine ecosystems. *Arctic and Alpine Research*, v.19(1):11-20.
- Bones, J. 1996. Light Writings, Microsoft Internet Explorer; <http://www.rt66.com/~jimbones>
- Bundrett, (spelled Brundrett in text) M., L. Melville, and L. Peterson, eds. 1994. *Practical Methods in Mycorrhiza Research*. Mycologue Publications, Ontario.
- Francis, R. and D.J. Read. 1995. Mutualism and antagonism in the mycorrhizal symbiosis, with special reference to impacts on plant community structure. *Canadian Journal of Botany*, v.73 (Suppl. 1):S1301-S1309.
- Francis, R. and D.J. Read. 1994. The contributions of mycorrhizal fungi to the determination of plant community structure. *Plant and Soil*, v.159:11-25.

- Harris, S. 1996. Faith in a Seedball. In: Dialogue, a publication of the New Mexico Water Dialogue, v.4(2):16-17.
- Menge, J.A. 1983. Utilization of vesicular-arbuscular mycorrhizal fungi in agriculture. *Canadian Journal of Botany*, v.61:1015-1024.
- Morton, J. 1998. Personal Communication. Department of Biology, West Virginia University, Morgantown, WV.
- Morton, J. 1996. INVAM Protocols for Producing Bulk Cultures. Microsoft Internet Explorer, <http://invam.caf.wvu.edu>.
- Reeves, F.B., Wagner, D., Moorman, T., and J. Kiel. 1979. The role of endomycorrhizae in revegetation practices in the semi-arid west: A comparison of incidence of mycorrhizae in severely disturbed vs. natural environments. *American Journal of Botany*, v.66(1):6-13.
- Sanders, I.R. and A.H. Fitter. 1992. The ecology and functioning of vesicular arbuscular mycorrhizas in coexisting grassland species: Seasonal patterns of mycorrhizal occurrence and morphology. *New Phytologist*, v.120 (4):517-524.
- Siguenza, C. Espejel, I., and E.B. Allen. 1996. Seasonality of mycorrhizae in coastal sand dunes of Baja-California. *Mycorrhiza* v.6 (2):151-157.

Using GIS Technology to Analyze and Understand Wet Meadow Ecosystems

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David Pawelek
Daniel Neary

Abstract—A Cibola National Forest wet meadow restoration was implemented as part of the Forest Road 49 enhancement near Grants, New Mexico. An Arc/View 3.0 Geographic Information System (GIS) was used to track the recovery of this ecosystem. Layers on topography, hydrology, vegetation, soils and human alterations were compiled using a GPS and commonly available data. Cartographic information allows visual interaction of natural features that could not be interpreted from tabular data sets. First results indicate that stream confinements by the railroad trestle, old channel fill, old two-track roads, Forest Road 49, and mis-graded construction affected the flow and location of spring floodwaters in 1998.

Agua Fria meadow is a small, 2.6 km² forest opening located in the Zuni Mountains 32 km southwest of Grants, New Mexico, and bisected by Forest Road (FR) 49 (Jemison and others 1998). It is representative of numerous fourth order streams in the Rio Grande basin affected by grazing, water erosion and changes in water flow due to human impacts (Jackson 1994a). The lower end of the meadow was blocked 3-15,000 years ago by one of the El Malpais sequence of lava flows (Mabery, 1997). Thick organic soil layers recently exposed by channel erosion suggest the area was a typical 'wet meadow', retaining much of the water that flowed into the area. Circa-1900 logging in the upper watershed, and the location of transportation routes could have contributed to preresoration conditions of increased surface runoff, elevated channel flow rates and channel erosion. The decreased elevation of the old channel could have lowered the water table across the meadow, with the net effect being a change towards a more xeric ecosystem.

Funds to reroute Agua Fria Creek were provided in 1995 via a Forest Road improvement project with the Federal Highway Department. The goal of the restoration design was to increase the period of flow through the meadow (Jackson, 1994b). Slower water velocity and more water absorption over a larger area of the meadow were planned through construction of a highly sinuous channel (fig. 1).

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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The new channel runs down the center of the meadow, 2-3 m in elevation above the old channel. It is only .60-.75 m deep in contrast to the old channel which was incised as much as 3 m in places (fig. 2). Thus the new channel has a much smaller cross sectional area which encourages flooding and water retention in the meadow.

Importance of GIS

As a technology, GIS is an information management and analysis tool (Harlin and Lanfear, 1993). Map layers and associated databases can be compiled and serve as reference tools for effective communication of past, present and potential conditions. Data incorporated into a GIS can include point data, such as photo-points or the location of objects and spatial data, such as historical landuse maps and vegetation coverages.

Environmental data frequently collected in wetland monitoring projects includes vegetation, soil moisture, stream channel profile and water table level (Brinson, 1996 and Harlin and Lanfear, 1993). The location and/or extent of these data can be mapped with a Global Positioning System (GPS) unit and presented in 2- and 3-dimensional models. GPS mapped data can be easily combined with existing GIS map layers to increase previous coverages and analyze spatial interactions between mapped features.

Questions that can be addressed using GIS/GPS are:

- How does elevation affect water flow across the meadow?
- Are the new channel elevations and grades adequate to meet restoration specifications?
- Why is the channel breached in some areas?
- What is the potential extent of the new wet meadow?
- How does soil moisture distribution across the meadow change over time?
- How does vegetation adjacent to the channel change over time?
- How does channel morphology change over time?
- How do past and present land uses (railroad, roads, borrow pits, etc.) affect current conditions?

Methods

A Trimble Geoexplorer II GPS with post-processing differential correction and Arc/View GIS 3.0 software were used to acquire the locations of the project fence perimeter, FR 49,



Figure 1—This photo shows the “green belt” surrounding the meanders of the newly installed channel. This channel is shallow and wide with 37 meanders in the study area. The old channel show in figure 1 is relatively straight and more deeply incised.



Figure 2—Previous restoration projects amplified erosion in the old channel on the south side of the meadow. This photo shows the ensuing escarpment, looking upstream.

two-track roads, stream channels, train trestle, borrow pit location, and the 1998 spring flood extent for Agua Fria meadow. In conjunction with a laser leveller, the GPS unit recorded point locations for a submeter accuracy surface elevation map. Point data collected includes the locations of stream flow measurements, head cutting, core sampled trees, rock weirs and carbon dated soils.

Results

A map of the flood water extent in the spring of 1998 was created by walking the perimeter of the flood areas with a GPS unit (fig. 3). The extent of the flood was visually identified by standing water, wet soils, soil deposits and soggy vegetation. Major breaches of the new channel are also identified on the map. This information will be important to track the success of the new channel, the vegetative response, and the reoccurrence of seasonal flooding. Previous human alterations act as constraining features to the water in Agua Fria meadow. Flooding is at least partially confined by the railroad bed, roads, and the old channel.

Personal observations during 1998 spring runoff demonstrated that rates of erosion and deposition can be very rapid at Agua Fria. Soil carbon dates for soil samples collected

between 75 and 90 cm below the soil surface at the lower end of the project area were dated at AD 1430-1670 and AD 770-380. Combined with other information about the area this information could help us determine the sequence of events that have taken place in the meadow.

Runoff water flowed at Agua Fria for approximately 2-3 months in the spring of 1998. Flood waters flowed above the bankfull stage and across the meadow for more than half the time. Variations in the gradient of the new channel from the project design caused water to flow into areas not predicted. For example, less slope than expected directly downstream of FR 49 and fill materials placed in the old channel, higher than the adjacent surface, directed over-bank flows away from the new channel into a two-track road.

Two-track roads above and below FR 49 partially diverted water away from the new stream channel. Above FR 49, a two-track that crossed the new channel caused more water to flow across rather than around a constructed channel meander. Below FR 49, flood water diverted onto a two-track road by gradient and fill variations flowed into the borrow pit (fig. 3). These diversions of water increased the area of the lands projected to be inundated with floodwaters, a major goal of the restoration. However, while increasing the extent of the areas flooded, these two-track roads have the

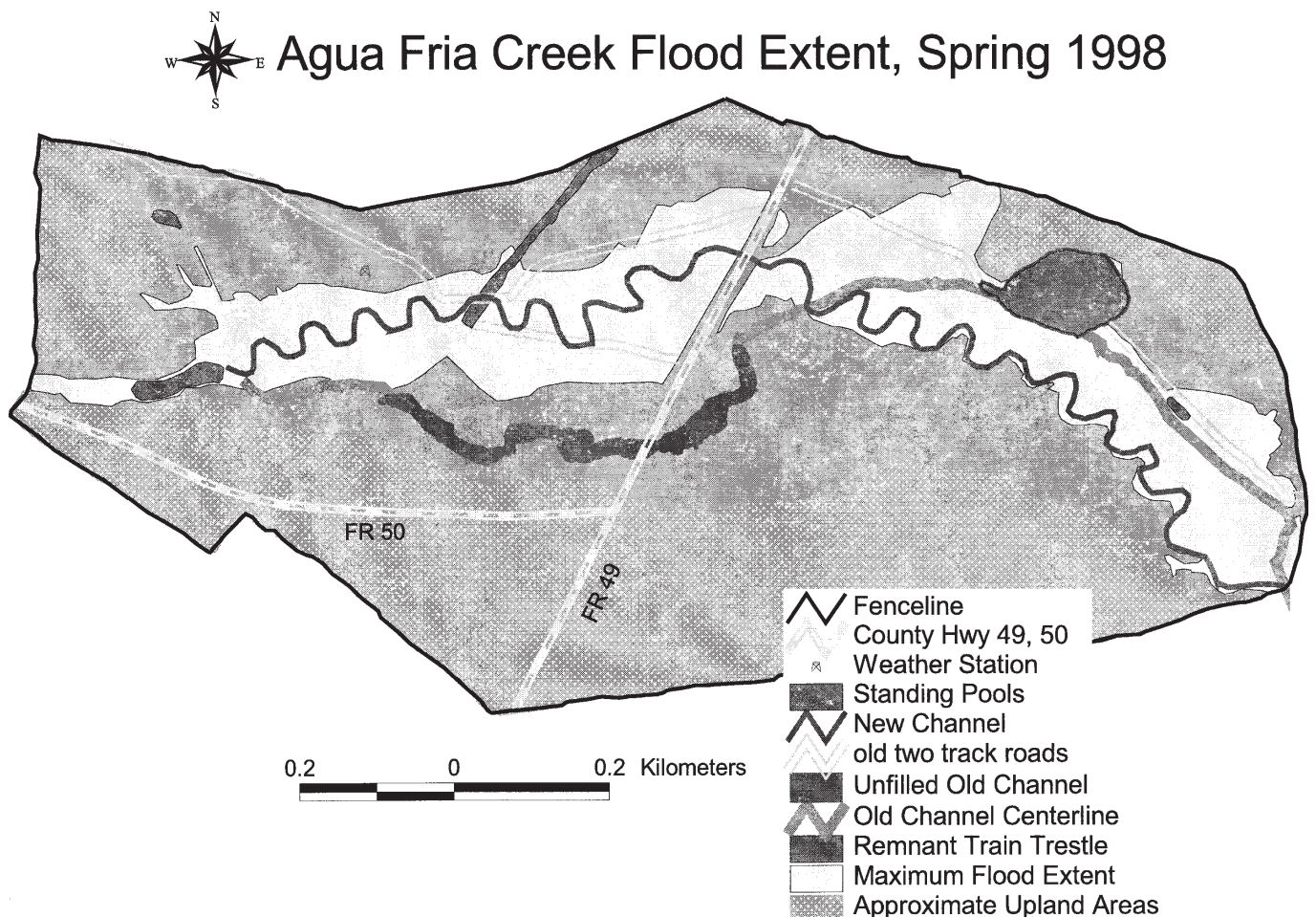


Figure 3—1998 spring Flood Map.

potential to be eroded into straight channel sections. Straight channel sections would allow water to flow quickly through them and could over time return the channel and meadow to pre-project conditions.

The over-bank flows downstream of FR 49 that were diverted into the borrow pit, filled the pit and flowed toward the lower end of the project area (fig. 3). These flows ran

across the surface and followed the course of the old stream channel, most of which had been previously filled in with soil from the borrow pit. Increased surface slope at the lower end of the study area caused overland flows to initiate erosion and headcutting in the area where the diverted water rejoined the new channel (fig. 4). By the time runoff stopped, headcuts had formed up to 1.50 m deep and 30 m to 50 m long (fig. 5).



Figure 4—Downstream of the new channel breach, below Forest Road 49, standing water and sheet flow cover the reseeded and filled old channel, during the spring of 1998.



Figure 5—Major erosion due to spring 1998 flooding. This photo is taken looking upstream from the fenceline project boundary. The second to last constructed concrete weir is in the center of the photograph.

Management Implications

GIS and GPS technology is becoming more commonly used as management and reference tools in the Southwest Region of the USFS. Currently an interoffice IBM system with Arc/Info, database management and statistical software is being by the USFS nationwide. This hardware and software upgrade will facilitate data transfer, analysis, storage, analysis and the creation of GIS products. This project will demonstrate how the successes and failures of ecosystem alterations can be studied and documented. This information will provide guidance for other projects that address similar issues and have access to similar technologies.

Future Work

GPS and GIS will continue to be used to collect, analyze and store information about Agua Fria meadow. In addition to the stream flow and climatic data being collected, continuous monitoring of watertable levels and soil moisture will be initiated in 1998. Vegetation cover and stream channel longitudinal profiles will be surveyed every spring and fall.

GIS coverages of natural and human induced attributes and interactions will continue to be compiled and analyzed to increase our understanding of the ecosystem functions at

work in Agua Fria meadow. Perhaps using GIS elevation maps and groundwater observation well information, water table elevations can be geographically hypothesized. Soil moisture and groundwater data may help validate possible ecosystem changes.

References

- Brinson, M. 1996. Assessing Wetland Functions Using HGM. *National Wetlands Newsletter*, Jan.-Feb. 1996, pg. 10-16.
- Harlin, J.M. and K.J. Lanfear (editors). 1993. *Proceedings of the Symposium on Geographic Information Systems and Water Resources*. May 14-17, 1993 Mobile, AL. Published by the American Water Resources Association, Bethesda, MD. pg 640.
- Jackson, F. (1994a) Zuni Mountains Road Reconstruction, Channel Restoration—Initial Studies. U.S. Department of Agriculture, Forest Service, Cibola National Forest, Albuquerque, NM.
- Jackson, F. (1994b) Zuni Mountains Road Reconstruction—Agua Fria Bridge Site Channel Restoration Design. U.S. Department of Agriculture, Forest Service, Cibola National Forest, Albuquerque, NM.
- Jemison, R., D. Neary, and D. Pawelek. 1998. *Effect of Geomorphic Controls and Human Interventions on Riparian Meadow Ecosystems in the Zuni Mountains of New Mexico—Study plan*. Rocky Mountain Research Station, US Forest Service. Albuquerque, NM.
- Mabery, Ken. 1997. *Natural History of El Malpais National Monument*, Bulletin 156, New Mexico Bureau of Mines and Mineral Resources, Albuquerque, NM.

Integrated Surface Management for Pipeline Construction: the Mid-America Pipeline Company Four Corners Project

Maria L. Sonett

Abstract—Integrated surface management techniques for pipeline construction through arid and semi-arid rangeland ecosystems are presented in a case history of a 412-mile pipeline construction project in New Mexico. Planning, implementation and monitoring for restoration of surface hydrology, soil stabilization, soil cover, and plant species succession are discussed. Planning phases included baseline survey for native plant community composition and noxious weed populations, seed mixture design, critical area identification, construction specifications for seeding, weed control and erosion controls, and information meetings. Implementation phases included daily inspection of equipment, seed quality and quantity, planting, mulch cover and anchoring, erosion control blankets, water diversion structures, and arroyo stabilization structures. Monitoring commitments for seeding success, noxious weed spread, and condition of erosion controls on public land were established for three years following project completion. Two years of noxious weed monitoring showed that most noxious weed populations appear to have been contained by project-specific weed management. One population of halogeton (*Halogeton glomeratus*) was contained after the first year but increased in area after the second year. Monitoring of seeding success will occur in a one-time assessment three growing seasons after completed seeding (1998).

With adequate time, drastically disturbed lands will heal unassisted by human intervention through successional development of plant communities. The rate of natural recovery in semi-arid environments is sometimes too slow to prevent an accelerated rate of soil erosion (Munshower, 1994). Further, natural recovery of a disturbed site may be arrested in the early stages of succession as first-stage exotic invaders develop into mono-cultures, and compete with desirable seral species for available resources (Richard Lee, personal communication).

Pipeline construction projects are commonly subject to environmental commitments in National Environmental Protection Act (NEPA) documentation. Environmental commitments frequently include requirements for the establishment of protective ground cover in the form of native perennial vegetation within a mandated period of time, often three years or less (Mid-America Pipeline Four Corners Project Environmental Assessment, Plan of Development, 1995). In semi-arid environments, where mean annual precipitation

is low, it is unlikely that these requirements can be met without the help of reclamation science and subsequent surface management.

The role of reclamation science is to augment the critical early stages of natural succession in a plan for re-establishment of a self-sustaining plant community. The plan should include three phases: 1) planning and design, 2) implementation, and 3) monitoring and evaluation. The plan should address the following surficial conditions and processes: 1) plant communities and vegetative cover, 2) surface soil condition and erosion control, and 3) invasive weed control. The success of any project utilizing such a method depends on both the quality of the individual components, and the degree to which these components are successfully integrated. Further, we found that plan integration must also mean that all three phases are integrated into the overall construction project schedule.

Mid-America Pipeline Four Corners Project

The Mid-America Pipeline Four Corners Project provides a case study of a surface reclamation and management effort that was successfully integrated into a well-executed pipeline construction project.

The project, starting at Huerfano, New Mexico and ending in Seminole, Texas, was constructed under a permit from the Farmington District of the United States Department of the Interior Bureau of Land Management. A new 12 inch line was installed into an existing right-of-way. Total project length was 412 miles, including a 10-mile lateral line. Project planning began in December 1994, and construction was completed in December 1995.

Pre-work Measures

Communication about desired goals and planned actions for reclamation and management of surface conditions is a critical component in successful implementation. Pre-job meetings with contractors and inspection personnel were used as a forum to introduce reclamation topics and required actions and to clarify coordination between construction personnel and reclamation personnel. This type of early communication made integration to a larger project easier.

Planning and design began with field reconnaissance to identify plant communities, areas of high erosion potential, and presence of noxious weed infestations (table 1). This information was then used to create reclamation specifications including seed mixtures, seeding techniques and equipment, erosion control techniques, and noxious weed management.

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Table 1—Weed species identified for control and management on the Mid-America Pipeline Four Corners Project, 1995. This list is based on a list of candidate species for the New Mexico noxious weed list for New Mexico, from Dr. Richard Lee, New Mexico State University Weed Control Scientist, November 1994.

Common name	Scientific name	Life cycle	Origin
African Rue	<i>Peganum harmala</i>	P	I - North Africa
Camelthorn	<i>Alhagi pseudalhagi</i>	P	I - Asia
Canada Thistle	<i>Cirsium arvense</i>	P	I - Eurasia
Dalmation Toadflax	<i>Linaria genistifolia</i> ssp. <i>dalmatica</i>	P	I - Europe
Diffuse Knapweed	<i>Centaurea diffusa</i>	P	I - Med.
Halogeton	<i>Halogeton glomeratus</i>	A	I - Asia
Jointed Goatgrass	<i>Aegilops cylindrica</i>	A	I - S. Europe
Leafy Spurge	<i>Euphorbia esula</i>	P	I - Eurasia
Malta Starthistle	<i>Centaurea melitensis</i>	A	I - Europe
Musk Thistle	<i>Carduus nutans</i> or <i>Carduus thoermeri</i>	B	I - S. Europe
Perennial Pepperweed	<i>Lepidium latifolium</i>	P	I - S. Europe
Purple Loosestrife	<i>Lythrum salicaria</i>	P	I - Europe
Purple Starthistle	<i>Centaurea calcitrapa</i>	A	I - Europe
Russian Knapweed	<i>Acroptilon repens</i>	P	I - Eurasia
Scotch Thistle	<i>Onopordum acanthium</i>	B	I - Europe
Spotted Knapweed	<i>Centaurea maculosa</i>	P	I - Eurasia
Teasel	<i>Dipsacus fullonum</i>	B	I - Europe
Whiteweed or Hoary Cress	<i>Cardaria draba</i>	P	I - Europe
Yellow Starthistle	<i>Centaurea solstitialis</i>	A	I - Europe
Yellow Toadflax	<i>Linaria vulgaris</i>	P	I - Eurasia

"A" - Annual, "B" - Biennial, "P" - Perennial, "I" - Introduced

Revegetation

Seven broad plant community classifications were done after William Dick-Pedie (1993). These included: Plains-Mesa Grassland, Plains-Mesa Sand Scrub, Southern Desert Grassland, Juniper Savanna, Coniferous and Mixed Woodland, Great Basin Desert Scrub, and Northern Desert Grassland. Project seed mixes included native, warm season perennial grasses, cool-season perennial grasses, perennial and annual forbs, and woody species referenced by Dick-Pedie as major plants comprising the selected plant community types. All seeded species were selected for ecological suitability and for palatability as forage or browse.

Revegetation efforts began in the first phase of construction with an operation called "double-ditching". "Double-ditching" is an industry term for topsoil removal during the right-of-way clearing and smoothing. Topsoil was removed and placed to one side of the pipeline trench. The next layer of soil was removed and placed in a separate pile.

Several months later, after the pipe is laid, the soil is replaced in the trench in the same order that it was removed, with the more fertile topsoil on top. These areas were then re-graded to match original site contours, and finish graded with a moto-grader. The moto-grader left a rough, deeply imprinted soil surface that was approved as the seedbed condition. Large soil particles and a rough surface provided excellent water infiltration, and protected the light, fluffy seed from high winds.

Seeding techniques and equipment were recommended based on soil type and slope conditions. The majority of the pipeline area was seeded with a heavy-duty rangeland drill, followed by application of vegetative mulch material such as straw or corn stalk in some areas.

During pre-construction mapping, the observed density of annual and perennial invasive weed species was greater at the edges of the right-of-way, possibly where seeding from previous pipeline construction had not extended into existing vegetation. This may have left a strip of unseeded, disturbed ground that was more susceptible to weed invasion. Seeding and mulching operations therefore were specified to be "knit" into the existing vegetation, in order to assure that no disturbed soil was left untreated.

Quality control was required for all re-vegetation materials. Mulch material was inspected at the producer's fields for weed content. Project requirements specified that materials be purchased from a producer who regularly managed for weeds, and whose fields were located in a designated "weed district," under the supervision of a county weed agent.

A random section of the project seed lots was also sampled for weed seed content. Although required standard testing was done by the seed supplier at certified laboratories, seed was "double-certified" to assure absence of potential problem species. Of the seed lots sampled, invasive weed species were found in two lots. These species were omitted from the seed mixes, and an appropriate replacement was approved by the permitting agency.

Erosion Control

Erosion control for upland areas included mulching with straw or chopped corn stalks, construction of water bars to direct flow off the right-of-way, and installation of erosion control blankets on steep slopes. Areas with slopes of greater than 15 percent were identified as high erosion risk, and were designated for broadcast seeding and application of

erosion control blankets. As the revegetation project progressed, other areas of high erosion risk were identified, and were stabilized with erosion control blankets.

Erosion control for riparian areas began with the preservation of existing riparian vegetation for habitat and bank stabilization. Three large rivers, the Rio Grande, the Rio Puerco, and the Pecos River, were crossed by a directional drilling method that minimizes impacts to the river channel and eliminates impacts to riverbank vegetation. The directional drill begins several hundreds of feet back from one bank, angles down and under the river bed, and re-emerges several hundred feet back from the opposite bank.

Where riparian vegetation was removed, banks were stabilized with rip-rap and seeded with native grass species. Riparian restoration included pole plantings of willow and cottonwood, at a replacement ratio of 10:1.

Ephemeral arroyo systems of sufficient magnitude to warrant concern about erosion were stabilized with small grade control structures made from either gabion baskets, or by native rock mined during trench excavation. Gabion baskets were placed following formal engineering designs, and rock was generally placed in smaller arroyos by informal field design.

Noxious Weed Management

Noxious weed management was intended to reduce or eliminate the spread of noxious weeds through earth-disturbing construction activities. Management included pre-construction mapping, chemical treatment of target weed populations, specifications requiring equipment cleaning, soil management during construction, and post-construction monitoring.

Four populations of noxious weed species were identified during pre-construction mapping. These populations are listed in table 2.

A mixture of Garlon (triclopyr) and 2,4-D was applied by a licenced applicator. Chemical application techniques varied according to the size and density of weed infestations. In some areas, target weed populations had not crowded out all other vegetation, so a spot spray was used to help conserve surrounding vegetation. In other areas, dense infestations that had out-competed desirable vegetation required a broadcast spray.

The small colony of musk thistle was removed by hand. Plants were placed in a sealed container, allowed to dry

within that container, and were subsequently burned in a 50-gallon drum by blow torch.

To limit the potential of weed spread by seed-infested soil on equipment, soil to a depth of 6"-8" was scraped and stockpiled at the edge of the working area. Stockpiled soils were flagged to prevent their re-location and to prevent access by vehicular traffic.

Equipment used for soil removal was cleaned immediately after use. Cleaning was performed by hand, and took place in the same general location as the stockpiled soils. Hand cleaning by brush and scraper was approved by the permitting agency as an alternative, cost-effective method for the bulldozer used in weed areas. The tracks and blade of the bulldozer were brushed off by hand-held brooms, and caked dirt was scraped off with a hand-held scraper blade. This method took an average of one-half hour per location.

Both plant and soil removal was planned to limit the distribution of seed by equipment into un-infested areas of the right-of-way.

Post-Construction Monitoring and Management

Post-construction monitoring for noxious weeds and for erosion control was carried out for three growing seasons following job completion.

Seeded stand success appeared promising in many areas after two growing seasons. In other areas, livestock utilization, lack of precipitation, and poor soils were noted as the probable causes of poor stand success. Final monitoring for seeded stand success will be carried out in 1998 by Bureau of Land Management range staff.

Prevention of noxious weed spread on the right-of-way was successful for Russian knapweed (*Acroptilon repens*) for all three years, and these populations were successfully eliminated by the third year. The population of halogeton (*Halogeton glomeratus*) was apparently contained for the first year after construction, but increased in area in the second year. Since the direction of population spread was opposite that of the direction of construction, livestock rather than equipment may be the agent of spread. The small colony of the biennial, musk thistle (*Carduus nutans*), was hand removed in the second year following construction and did not reoccur in the third year.

Table 2—Weed species identified on the Mid-America pipeline right-of-way during pre-construction survey, July-August, 1995.

Scientific name	Common name	Approximate size of infestation	Approximate density of infestation
<i>Halogeton glomeratus</i>	Halogeton	scattered colonies over 100-200 acres	1-5/ft ²
<i>Carduus nutans</i>	Musk thistle	4000 ft ²	15-20 individuals
<i>Acroptilon repens</i>	Russian knapweed	720 ft ²	1/ft ²
<i>Acroptilon repens</i>	Russian knapweed	3 scattered colonies of approx. 3000 ft ² over 3 acres	2.5/ft ²

Erosion control measures (erosion blanketed slopes and grade control structures) were assessed by air survey. Areas showing erosion or damaged measures were reported to an on-call contractor, who carried out repairs.

Conclusions

Integrated surface management provides a comprehensive method to assist early stages of natural plant community succession and site stabilization. An integrated approach includes three phases: 1) pre-construction measures, such as coordination, site survey, and design of seed mixtures and erosion control requirements; 2) implementation of plans and designs during construction; and, 3) post-construction monitoring and adjustment of non-satisfactory areas.

The term “integrated” applies to the integration of three closely related surficial processes: 1) soil erosion; 2) plant

community dynamics; and 3), control of exotic invasive plant species. It also applies to the integration of the reclamation effort into the overall construction project, particularly in terms of scheduling and cooperation of different construction phases.

References

- Bureau of Land Management, Environmental Assessment for the Mid-America Four Corners Pipeline Loop Project. June 1995. Volume 1
- Dick-Pedie, William A. 1993. New Mexico vegetation, past present and future. University of New Mexico Press, Albuquerque, New Mexico.
- Munshower, Frank F. 1994. Practical Handbook of Disturbed Land Revegetation. CRC Press, Inc. pp. 2-4.
- Lee, Richard Personal Communication, 1995. New Mexico State Cooperative Extension Service Weed Scientist, New Mexico State University, Las Cruces, New Mexico.

Biodiversity and Endangered Species



Maternity Roosts of Bats at the Bosque Del Apache National Wildlife Refuge: a Preliminary Report

Alice Chung-MacCoubrey

Abstract—Historic and recent changes in the structure, composition, and distribution of riparian forests have likely influenced populations of bats through their effects on habitat quality for reproductive females. This project seeks to identify natural structures used by maternity colonies, determine criteria used in the selection of these roosts, and interpret how historic and current human activities may positively or negatively impact bat populations in the bosque. This paper reports first season results from this ongoing project. Thirteen reproductive female bats (5 little brown myotis, 5 Yuma myotis, 1 red bat, and 2 pallid bats) captured on the Bosque del Apache National Wildlife Refuge in the summer of 1997 were radiotracked daily to their maternity roosts. Four little brown and Yuma myotis colony roosts were found. Colony size ranged from 90 to over 1800 bats. Two colonies were in manmade structures. Two other colonies and numerous solitary roosts were found in natural structures (dead cottonwoods). A pallid bat roosted in a rocky butte, and the red bat roosted in the foliage of a large, live cottonwood. Six of the nine tree roosts were in burned areas of forests directly along the river. Individuals and colonies of little brown and Yuma myotis used under-bark crevices and snags rather than more permanent types of roosts. Additional data from subsequent years will help determine whether the use of ephemeral bark roosts, snags, and riverside forests are characteristic of bat roost selection in the bosque.

Riparian-associated bats may be found in the bosque where suitable foraging and roosting habitat exists along relatively permanent bodies of water. However, historic and recent human activities have changed the structure, composition, and distribution of these forests in New Mexico. The effects of these changes on the population status of bats have yet to be determined. Because of their unusually low reproductive rate (typically one offspring per year), bat populations can easily be affected by events that alter the availability and distribution of resources to reproductive females. Suitable roosts and a sufficient diet are critical to successful reproduction by females (Humphrey 1975, Racey 1982). Historic and ongoing changes in riparian forest structure, composition, and distribution due to agriculture, flood control, channelization, demand for fuel and wood products, and exotic plant invasion (Scurlock 1995) have undoubtedly

affected the abundance and diversity of roosts and foods available to female bats during the summer. Hence, the reproductive success and status of bat populations along the Rio Grande have likely been impacted. Yet it is difficult to assess the magnitude of these historic impacts or abate future impacts because the resources critical to successful reproduction by bats in bosque habitats are not known. The goal of this project is to identify roost structures used by reproductive females, determine how historic, ongoing, and future changes in the structure and composition of the bosque may benefit or harm the resident bat communities, and provide recommendations on how to improve bat habitat.

Specific objectives of this project in progress include 1) identifying and characterizing structures used as colony and solitary maternity roosts by bats and the general environment surrounding roosts and 2) describing roost behaviors of reproductive female bats in the bosque. With this information, recommendations will be made on how land management activities may be used to positively affect critical resources for bats and how to abate negative effects on bat habitat in the bosque.

Methods

Maternity roosts were identified by radiotagging reproductive female bats and locating them at their daytime roosts. Field work was conducted on the Bosque del Apache National Wildlife Refuge (Bosque del Apache NWR) from June to August 1997. Reasons for the selection of this site include the presence of native bosque, remoteness from urban influences, and the potential to collaborate with other ongoing wildlife and vegetation studies. Candidates for radiotagging were captured by placing mist nets over various types of water following the method of Kunz and Kurta (1988). Net sites throughout the refuge included flooded water management units, canals, shallow sections of the Rio Grande, and flight corridors. Nets were opened at sunset and closed after midnight. Information on the species, sex, age, reproductive status, and weight of all bats captured was recorded.

To identify maternity roosts, pregnant, lactating, or postlactating females were fitted with radiotransmitters. One to four reproductive females were radiotagged in a single night. Fur was clipped from between the shoulder blades, and a 0.50 - 0.67 g radiotransmitter (Holohil Systems Ltd.) was glued to the back of the bat with surgical adhesive (Skin-Bond®) (Wilkinson and Bradbury 1988). Bats were released after the glue dried (approximately 30 minutes). Radiotagged bats were located each day until signals were lost or radios were retrieved.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Each roost and its immediate surroundings were evaluated, and the number of bats exiting at dusk was counted to determine total roost occupancy. Information on the number of roosts used by each bat, the type and location of roosts, and roost fidelity were collected. Roost locations were recorded with a global positioning system units (Trimble Geoplotter GPS and Pathfinder Basic Plus).

Preliminary Results and Discussion

Mist Net Captures

From 11 June to 30 July 1997, we mist netted 13 nights at 9 sites. These sites included 4 flooded water management units, 2 streams along flight corridors, 2 sections of river, and 1 section of canal. During the earlier part of the netting period, capture success was low because water was available throughout the refuge (river level was up and many management units were flooded). However, as the summer progressed, river level went down, many management units were drained, and overall water availability decreased on the refuge. Accordingly, capture success improved. From the 13 net nights, we captured and identified 130 bats of 6 species (table 1). The most abundant species caught was the Mexican free-tailed bat (*Tadarida brasiliensis*). Moderate numbers of little brown myotis (*Myotis lucifugus*) and Yuma myotis (*M. yumanensis*) were captured. A small number of pallid bats (*Antrozous pallidus*) and a single small-footed myotis (*M. ciliolabrum*) and red bat (*Lasiurus borealis* or *L. blossevilli*) were captured. At the time of capture, field identification of the red bat, a lactating female, to one of the two species (*L. borealis* or *blossevilli*) was not possible. This individual was radiotagged and thus not available for a voucher specimen. Seventy-seven percent of the total bats captured were female, and 62 percent of these females were reproductive (pregnant, lactating, or postlactating).

Little brown myotis, Yuma myotis, hoary bats (*L. cinereus*) and Mexican free-tailed bats were reported previously on the refuge by Findley and others (1975). Reith (1982) later identified pallid bats as also present on the refuge. Recently, Valdez and others (in press) reported four previously undocumented species on the refuge: fringed myotis (*M. thysanodes*), silver-haired bat (*Lasionycteris noctivagans*), eastern red bat (*L. borealis*), and Townsend's big-eared bat (*Corynorhinus townsendii*). The female eastern

red bat captured by Valdez and others (in press) was not reproductive. The present study is the first to document the presence of a small-footed myotis and a reproductive red bat on the refuge.

Maternity Roosts Located

From bats captured during these mist netting sessions, 13 pregnant or lactating females were selected for radiotracking. Five little brown myotis (2 pregnant, 3 lactating), five Yuma myotis (1 pregnant, 3 lactating, 1 postlactating), two pallid bats (both lactating), and one lactating red bat were radiotagged. A radiotransmitter weight not exceeding 5 percent of the bat's body weight has been recommended to minimize effects on behavior and activities (Aldridge and Brigham 1988). In this study, transmitter weight was well below the recommended maximum of 5 percent for the larger species (pallid bats and red bat). For the smaller bats (little brown and Yuma myotis), transmitter weight ranged from 5.1-8.6 percent of the bat's body weight. Brigham and others (1997) did not report any adverse effects on reproductive female *Myotis californicus* tagged with transmitters 8-9 percent of their body weight. Additional research is needed to clarify the effects on and tolerances of bats to variable loads, and further miniaturization in transmitter size will allow researchers to minimize the effects of radiotagging on bats.

Eighteen roosts were located from the 13 radiotagged bats. One pallid bat was not relocated. Only one or two roosts were typically found per bat because either the signal disappeared after the second roost was found or some bats rarely moved during the entire tracking period. Two colony roosts were found repeatedly from 7 independently radiotagged bats. Thus only 13 unique roosts were found. Four were maternity colonies, and nine were solitary roosts. Two of the colony roosts were in manmade structures.

The lactating red bat was the second red bat captured at the Bosque del Apache NWR and the first to be radiotracked in the state. The red bat roosted high within the canopy of a large, live Fremont's cottonwood (*Populus fremontii*) (table 2). This cottonwood was part of a small, isolated cottonwood stand along the river surrounded by dense saltcedar (*Tamarix* spp.). The roosting behavior of this red bat is consistent with the foliage roosting behavior of this genus (Barbour and Davis 1969).

Table 1—Species, sex, and reproductive status^a of 130 bats captured during 13 mist netting events at the Bosque del Apache National Wildlife Refuge between June and August 1997.

Species	Female			Male			Total individuals
	Nonrepro	Repro	Juvenile	Nonrepro	Repro	Juvenile	
<i>Tadarida brasiliensis</i>	23	39	0	3	4	0	69
<i>Myotis lucifugus</i>	4	12	4	5	2	3	30
<i>Myotis yumanensis</i>	2	6	6	1	0	7	22
<i>Antrozous pallidus</i>	1	3	1	1	0	1	7
<i>Myotis ciliolabrum</i>	0	1	0	0	0	0	1
<i>Lasiurus borealis</i> or <i>L. blossevilli</i>	0	1	0	0	0	0	1

^aNonrepro = nonreproductive adult female or male. Repro = pregnant, lactating, or postlactating adult female or scrotal adult male. Juvenile = juvenile male or female young of the year.

Table 2—Description of roosts used by radiotagged, reproductive females of 4 species of bats at the Bosque del Apache National Wildlife Refuge.

Bat species ^a	Colony/solitary	# of bats	Roost type	D.b.h.(cm) ^b	Height(m)	Status
<i>Myotis lucifugus</i> (L)	Colony	507	<i>Populus fremontii</i>	80	14.4	dead
<i>Myotis lucifugus</i> (P)	Colony	90	<i>Populus fremontii</i>	50	21.6	dead
<i>Myotis lucifugus</i> (P)	Solitary	—	<i>Populus fremontii</i>	22	4.4	dead
<i>Myotis lucifugus</i> (L)	Solitary	—	<i>Populus fremontii</i>	63	26.0	dead
<i>Myotis lucifugus</i> (L)	Solitary	—	<i>Populus fremontii</i>	53	22.2	dead
<i>Myotis lucifugus</i> (L)	Solitary	—	<i>Populus fremontii</i>	32	20.2	dead
<i>Myotis yumanensis</i> (L)	Colony	>250	Concrete bridge	—	—	—
<i>Myotis yumanensis</i> (P)	Solitary	—	<i>Populus fremontii</i>	28	16.5	dead
<i>Myotis yumanensis</i> (L)	Solitary	—	<i>Populus fremontii</i>	—	—	dead
<i>M. lucifugus</i> & <i>M. yumanensis</i> (P, L)	Colony	>1800	Church roof/steeple	—	—	—
<i>Antrozous pallidus</i> (L)	Solitary	—	Rock crevice	—	—	—
<i>Antrozous pallidus</i> (L)	Solitary	—	Rock crevice	—	—	—
<i>Lasiurus borealis</i> / <i>blossevillei</i> (L)	Solitary	—	<i>Populus fremontii</i>	76	18.0	live

^aReproductive status of the radiotagged bat is in parenthesis. P = pregnant, L = lactating

^bD.b.h. = diameter at breast height

The lactating pallid bat was found in 2 separate rock crevices on the 2 days that it was relocated (table 2). These roosts were approximately 200 m apart on a lone rocky butte surrounded by grassland approximately 0.75 km east of the river. The use of crevices in vertical rock faces and cliffs is typical roosting behavior for pallid bats (Vaughan and O'Shea 1976).

Ten little brown and Yuma myotis roosts were found, four of which were colonies (table 2). Two little brown myotis colonies were found under the sloughing bark of cottonwoods killed in the 1996 fire. Occupancy at these two colonies declined from 507 and 90 bats in late June/early July to 50 and 0, respectively, in the first week of August. The 90-bat colony roost stood in the middle of an open grassy field. The 507-bat colony stood amongst a burned, dead stand of large and small cottonwoods along the river. The third colony, which consisted of over 250 Yuma myotis, roosted in deep, vertical crevices (1.5 cm wide) running the length of the underside of a small concrete bridge close to the river. The fourth colony roost was located 8 miles north of the refuge in the steeples and under the corrugated metal roofing of a local church. Over 1800 Yuma and little brown myotis shared this roost, but it is not known whether the two species segregated within the building. A dead Mexican free-tailed bat of unknown sex was also found in one of the steeples, suggesting that Mexican free-tails may also occasionally share this roost.

Six solitary roosts of Yuma and little brown myotis were located under the bark or in hollows of smaller cottonwood snags, also killed by the 1996 fire (table 2). The trees used as solitary roosts were generally of smaller d.b.h. ($\bar{x}$ = 39.6, SE = 7.84 cm, N = 5) than trees used as colony roosts ($\bar{x}$ = 65 cm, N = 2).

Most of the tree roosts (7 of 9 roosts) were in forests bordering the east and west side of the river. Within the Bosque del Apache NWR, forests directly along the river are relatively contiguous and unmanipulated. Forest types along the river include dense saltcedar stands, mixed cottonwood and saltcedar habitat, patches of mature cottonwood, and

burned cottonwood stands with new saltcedar saplings. To the west of the river and its associated riverside forest, the refuge is a mix of wetland, grassland, agricultural, and forested habitats. Forest patches are of small to medium size, scattered, and disconnected relative to the forest along the river. Only one colony and one solitary roost were found in these patches, perhaps due to their discontinuity with other forest or perhaps as a result of the sampling error. If not the result of sampling error, the predominance of roosts in riverside forest may indicate the need for contiguous forest stands which provide food and cover for roosting, commuting, and foraging. The capture of several Yuma and little brown myotis in riverside forest 8 miles south of the church colony they used indicates that these bats travel substantial distances while feeding in this habitat. Roosts were not found in pure saltcedar stands or mixed cottonwood/saltcedar stands, perhaps due to the dense understory that would make flight difficult.

The manmade structures used as colony roosts by little brown and Yuma myotis in this study are consistent with the known roosting habits of these species. Nursery roosts of Yuma myotis are commonly found in buildings, under bridges, and in caves and mines (Barbour and Davis 1969). Nursery roosts of little brown myotis have been found in buildings, under roofs, in attics, tree hollows, and other crevices with suitable temperature regimes (Fenton and Barclay 1980).

Ephemeral roosts are associated with high roost lability in bats, and more permanent structures are associated with high roost fidelity (Lewis 1995). Roosts of little brown myotis found in forest along the Rio Grande were under the bark or in crevices of dead trees within burned cottonwood stands. Reasons for using these ephemeral roosts may include decreased commuting costs to foraging areas, lower ectoparasite levels and a higher abundance and availability of ephemeral sites (Lewis 1995). The use of ephemeral tree roosts (for example under bark of snags) rather than more permanent tree roosts (for example hollows in live cottonwoods) may be due to a lower availability or suitability of the latter type. Permanent structures such as the church and bridge

allow higher roost fidelity, the benefits of which include reduced costs in roost searching, greater site familiarity, and the ability to maintain social relationships (Lewis 1995). Year to year site fidelity of these roosts will be assessed by returning to colony roosts in subsequent years and assessing occupancy.

The results of this single season of radiotracking give preliminary data on the roosting habits of Yuma and little brown myotis, red bats, and pallid bats on the Bosque del Apache NWR and its surrounding area. Additional maternity colony and solitary roosts must be located to better understand which roosts are selected by reproductive females, what characteristics make roosts suitable, how site fidelity or lability is associated with roost type, and how roost resources may be partitioned among species. With future field seasons, roost selection and behavior of these species on the Bosque del Apache NWR will be better and more conclusively characterized.

References

- Aldridge, H. D. J. N. and R. M. Brigham. 1988. Load carrying and maneuverability in an insectivorous bat: a test of the 5 percent "rule" of radiotelemetry. *J. Mammal.* 69:379-382.
- Barbour, R. W. and W. H. Davis. 1969. *Bats of America*. University Press of Kentucky, Lexington.
- Brigham, R. M., M. J. VonHof, R. M. R. Barclay, and J. C. Gwilliam. 1997. Roosting behavior and roost-site preferences of forest-dwelling California bats (*Myotis californicus*). *J. Mammal.* 78:1231-1239.
- Fenton, M. B. and R. M. R. Barclay. 1980. *Myotis lucifugus*. *Mammalian Species* 142: 1-8.
- Findley, J. S., A. H. Harris, D. E. Wilson, and C. Jones. 1975. *Mammals of New Mexico*. University of New Mexico Press, Albuquerque.
- Humphrey, S. R. 1975. Nursery roosts and community diversity of nearctic bats. *J. Mammalogy* 56:321-346.
- Kunz, T. H. and A. Kurta. 1988. Capture methods and holding devices. Pp. 1-30 in T. H. Kunz, ed. *Ecological and behavioral methods for the study of bats*. Smithsonian Institution Press, Washington, D.C.
- Lewis, S. 1995. Roost fidelity of bats: a review. *J. Mammalogy* 76:481-496.
- Racey, P. A. 1982. Ecology of bat reproduction. Pp. 57-104 in T. H. Kunz, ed. *Ecology of bats*. Plenum Press, New York.
- Reith, C. C. 1982. Insectivorous bats fly in shadows to avoid moonlight. *J. Mammal.* 63: 685-688.
- Scurlock, D. 1995. Environmental history. Pp.12-28 in D. M. Finch and J. A. Tainter, eds. *Ecology, diversity, and sustainability of the Middle Rio Grande Basin*. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-GTR-268. Ft. Collins, CO. 186 pp.
- Valdez, E. W., J. N. Stuart, and M. A. Bogan. In press. Additional records of bats from the Middle Rio Grande Valley, New Mexico. *Southwestern Naturalist*.
- Vaughan, T. A. and T. J. O'Shea. 1976. Roosting ecology of the pallid bat, *Antrozous pallidus*. *J. Mammalogy* 57:19-42.
- Wilkinson, G. S. and J. W. Bradbury. 1988. Radiotelemetry: techniques and analysis. Pp. 105-124 in T. H. Kunz, ed. *Ecological and behavioral methods for the study of bats*. Smithsonian Institution Press, Washington, D.C.

Bird Migration Through Middle Rio Grande Riparian Forests, 1994 to 1997

Michael D. Means
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Abstract—Expanding human populations in the middle Rio Grande have increased demands on water, land, and other resources, potentially disrupting bird migration activities. From 1994 to 1997, a total of 26,350 birds of 157 species were banded and studied. Results include species composition, timing of migration, and habitat use. Recommendations for managers are included.

Although quantitative accounts of landbird migration along the middle Rio Grande riparian corridors in the literature are rare, the use of the Rio Grande as a migratory route by landbirds is an acknowledged behavior of southwestern birds (Yong and Finch 1997, Yong and others 1998, Finch and Yong *in press*). The availability of food, water, cover, resting sites and a suitable north-south route along the river provides potential stopover resources for neotropical migrants such as flycatchers, warblers, and vireos and short-distance migrants such as many sparrow species. Expanding human populations in the middle Rio Grande have placed increasing demands on water, land, and other resources associated with riparian habitats. Water management, recreation, transportation, grazing, urban development, and invasion of exotic plant species alter these riparian habitats, potentially disrupting bird migration activities. How habitat changes have affected or will affect landbirds migrating through the middle Rio Grande is unclear (Finch and others 1995).

In spring 1994, we initiated a study to investigate the use of the middle Rio Grande riparian corridors as stopover habitat by neotropical and short-distance landbird migrants. This study is now in its fifth year. We have also been cooperating with Rio Grande Bird Research, Inc. by adding to and analyzing a 17-year (1981-1997) capture data set of migrating landbirds at the Rio Grande Nature Center in Albuquerque, New Mexico. The objective of this paper is to update our earlier reports (Finch and others 1995, Finch and Yong *in press*) on species composition, relative abundance, timing of migration, and general habitat use along the middle Rio Grande.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Methods

Study Sites

Our study sites were located at the Bosque del Apache National Wildlife Refuge (N33° 48' and W106° 52'), Socorro, NM, and the Rio Grande Nature Center (N35° 07' and W106° 41'), Albuquerque NM (fig. 1). Data were collected in spring (early April through early June) and in fall (early August through early November) 1994-1997. The Rio Grande Nature Center site was not studied during the spring of 1997. Both sites contained older Fremont cottonwood (*Populus fremontii*) forests and some younger forests of cottonwood, Gooding willow (*Salix gooddingii*), Russian olive (*Elaeagnus angustifolia*) and salt cedar (*Tamarix pentandra*). Sites also contained agricultural fields and riparian edges of coyote willow (*Salix exigua*). The Bosque del Apache site also included a homogeneous stand of salt cedar. Vegetation structure, plant species composition and tree size were measured to compare habitat characteristics.

Mist Netting

Between 20 and 40 nylon mist-nets (12 x 2.6 meter with 30 mm and 36 mm mesh) were used at each site to capture (and recapture) landbird migrants. Each net was set up 15 minutes before official sunrise and closed 6 hours later. The birds were removed from the nets, identified, measured and released as quickly and safely as possible. For more information about netting and banding procedures at our sites, see Kelly and Finch (1999 in this volume) and Finch and Kelly (1999 in this volume).

Point Counts

Sixteen transects were established in the dominant vegetation types in these areas: agricultural field edges, cottonwood, screwbean mesquite (*Prosopis pubescens*), mixed cottonwood, salt cedar and coyote willow. Each transect was 1 kilometer long and had point count stations located at 200 meter intervals (6 stations per transect). Birds were counted for five minutes at each station and birds detected between stations were also recorded. Behaviors and habitat use by birds were also recorded.

Results and Discussion

Numbers of Species and Captures

We banded a total of 26,350 birds of 157 species from 1994-1997, of which 6,000 (22.7 percent) of these were recaptures (table 1). Fewer spring birds were banded (21 percent) than

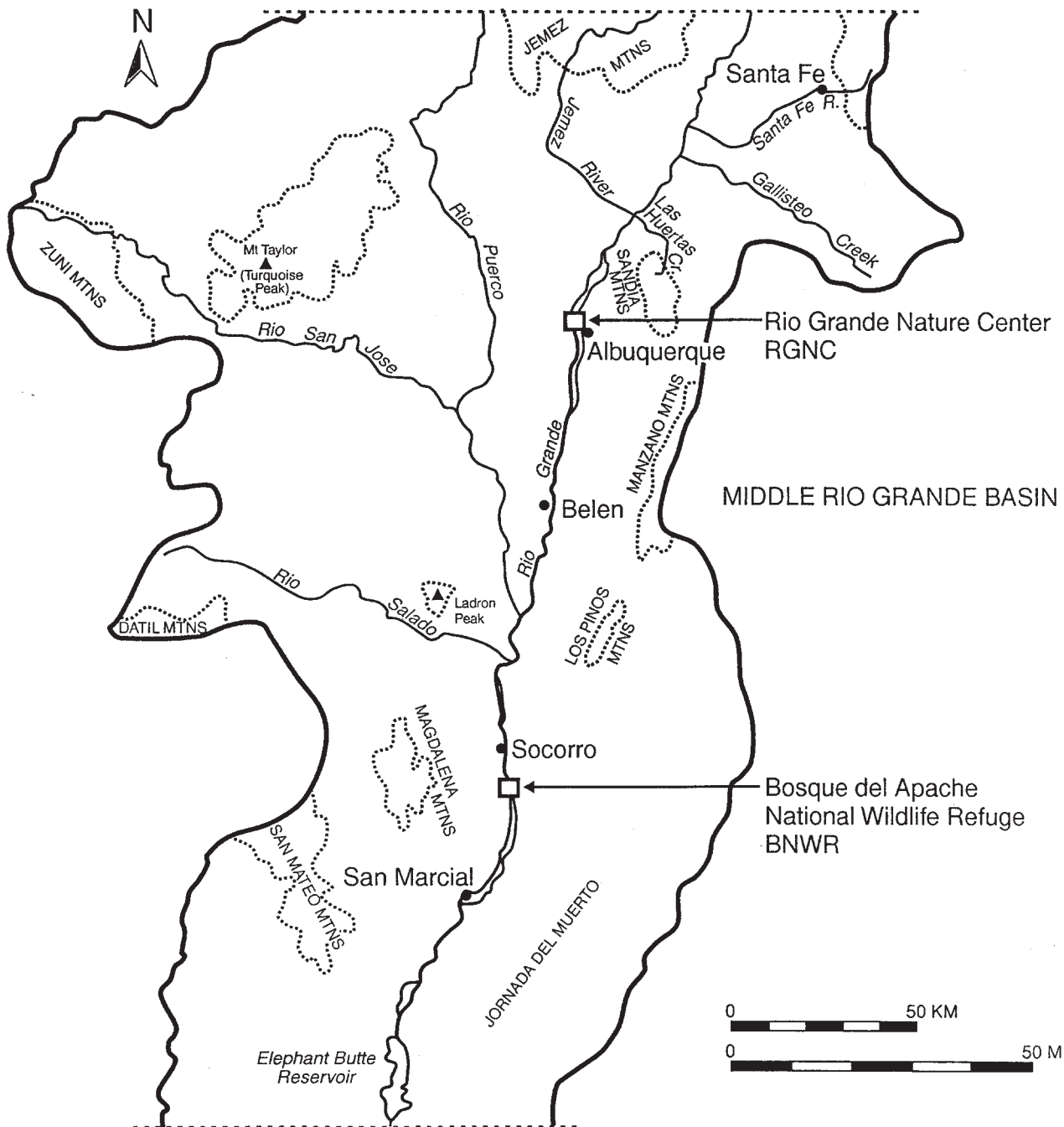


Figure 1—Study Sites: Bosque del Apache National Wildlife Refuge and Rio Grande Nature Center, NM.

fall birds (79 percent). This is because large numbers of hatch-year birds migrate south in the fall, increasing the number of fall captures. The majority of recaptures were resident breeders or winter residents. The most abundant neotropical migrants that return each year to breed at these sites were Common Yellowthroat (*Geothlypis trichas*), Blue Grosbeak (*Guiraca caerulea*), Black-Headed Grosbeak (*Pheucticus melanocephalus*) and Summer Tanager (*Piranga rubra*). The two most commonly recaptured short-distance migrants breeding in the areas were Spotted Towhee (*Pipilo erythrophthalmus*) and Bewick's Wren (*Thryomanes bewickii*).

We detected year-to-year fluctuations in species richness, numbers of captures, and age and sex ratios for our two sites. These fluctuations appeared to correspond to amounts of rainfall before and during the migration periods and may have influenced how concentrated migrants were relative to water sources. For example we have had much higher capture rates in drought years than wetter years. In addition, capture rates were generally higher at the Rio Grande Nature Center site in Albuquerque NM than at the Bosque del Apache. The Nature Center is surrounded by urban development whereas the Bosque del Apache is in a rural

Table 1—Total number of birds captured and banded, by family, at the Bosque del Apache National Wildlife Refuge and Rio Grande Nature Center from 1994 through 1997.^a

Common name	Family	Captures	Common name	Family	Captures
Sharp-shinned Hawk	Accipitridae	16.00	House Finch	Fringillidae	335.00
Red-tailed Hawk	Accipitridae	14.00	American Goldfinch	Fringillidae	297.00
Cooper's Hawk	Accipitridae	9.00	Cassin's Finch	Fringillidae	6.00
Swainson's Hawk	Accipitridae	5.00	Evening Grosbeak	Fringillidae	1.00
Ferruginous Hawk	Accipitridae	4.00	White-winged Crossbill	Fringillidae	1.00
Northern Harrier	Accipitridae	2.00	Barn Swallow	Hirundinidae	41.00
Common Bushtit	Aegithalidae	51.00	Northern Rough-winged Swallow	Hirundinidae	27.00
Belted Kingfisher	Alcedinidae	8.00	Bank Swallow	Hirundinidae	1.00
Common Nighthawk	Caprimulgidae	1.00	Violet-green Swallow	Hirundinidae	1.00
Lazuli Bunting	Cardinalidae	635.00	Red-winged Blackbird	Icteridae	255.00
Blue Grosbeak	Cardinalidae	512.00	Bullock's Oriole	Icteridae	87.00
Black-headed Grosbeak	Cardinalidae	366.00	Brown-headed Cowbird	Icteridae	55.00
Indigo Bunting	Cardinalidae	36.00	Great-tailed Grackle	Icteridae	17.00
Lark Bunting	Cardinalidae	14.00	Yellow-headed Blackbird	Icteridae	14.00
Painted Bunting	Cardinalidae	6.00	Western Meadowlark	Icteridae	9.00
Pyrrhuloxia	Cardinalidae	4.00	Common Grackle	Icterida	8.00
Rose-Breasted Grossbeak	Cardinalidae	3.00	Orchard Oriole	Icteridae	3.00
Dicksissel	Cardinalidae	2.00	Northern Mockingbird	Mimidae	22.00
Brown Creeper	Certhiidae	29.00	Gray Catbird	Mimidae	18.00
Killdeer	Charadriidae	7.00	Brown Thrasher	Mimidae	1.00
Mourning Dove	Columbidae	47.00	Crissal Thrasher	Mimidae	1.00
White-winged Dove	Columbidae	3.00	Sage Thrasher	Mimidae	1.00
Common Ground Dove	Columbidae	1.00	Mountain Chickadee	Paridae	41.00
Chihuahuan Raven	Corvidae	24.00	Black-capped Chickadee	Paridae	31.00
Scrub Jay	Corvidae	24.00	Plain Titmouse	Paridae	1.00
Western Scrub Jay	Corvidae	3.00	Wilson's Warbler	Parulidae	3771.00
American Crow	Corvidae	1.00	MacGillivray's Warbler	Parulidae	1372.00
Yellow-billed Cuckoo	Cuculidae	16.00	Orange-crowned Warbler	Parulidae	871.00
Greater Roadrunner	Cuculidae	7.00	Audubon's Warbler	Parulidae	822.00
Chipping Sparrow	Emberizidae	2722.00	Yellow Warbler	Parulidae	572.00
Gambel's White-crowned Sparrow	Emberizidae	1660.00	Common Yellowthroat	Parulidae	279.00
Oregon Junco	Emberizidae	779.00	Virginia's Warbler	Parulidae	265.00
Lark Sparrow	Emberizidae	576.00	Yellow-breasted Chat	Parulidae	73.00
Brewer's Sparrow	Emberizidae	557.00	Myrtle Warbler	Parulidae	60.00
Song Sparrow	Emberizidae	468.00	Northern Waterthrush	Parulidae	37.00
Lincoln's Sparrow	Emberizidae	464.00	Townsend's Warbler	Parulidae	17.00
Mountain White-crowned Sparrow	Emberizidae	405.00	Ovenbird	Parulidae	15.00
Savannah Sparrow	Emberizidae	317.00	Nashville Warbler	Parulidae	10.00
Spotted Towhee	Emberizidae	297.00	Lucy's Warbler	Parulidae	8.00
Vesper Sparrow	Emberizidae	251.00	American Redstart	Parulidae	5.00
Green-tailed Towhee	Emberizidae	241.00	Black-throated Gray Warbler	Parulidae	5.00
Clay-colored Sparrow	Emberizidae	213.00	Black-and-white Warbler	Parulidae	4.00
Gray-headed Junco	Emberizidae	168.00	Prothonotary Warbler	Parulidae	4.00
White-crowned Sparrow	Emberizidae	58.00	Hooded Warbler	Parulidae	3.00
White-throated Sparrow	Emberizidae	15.00	Kentucky Warbler	Parulidae	3.00
American Tree Sparrow	Emberizidae	6.00	Magnolia Warbler	Parulidae	3.00
Canyon Towhee	Emberizidae	6.00	Blue-winged Warbler	Parulidae	2.00
Black-throated Sparrow	Emberizidae	4.00	Chestnut-sided Warbler	Parulidae	2.00
Dark-eyed Junco	Emberizidae	3.00	Golden-winged Warbler	Parulidae	2.00
Grasshopper Sparrow	Emberizidae	3.00	Yellow-rumped Warbler	Parulidae	2.00
Sage Sparrow	Emberizidae	3.00	Bay-breasted Warbler	Parulidae	1.00
Slate-colored Junco	Emberizidae	3.00	Black-throated Blue Warbler	Parulidae	1.00
Swamp Sparrow	Emberizidae	3.00	Blackburnian Warbler	Parulidae	1.00
Golden-crowned Sparrow	Emberizidae	2.00	Canada Warbler	Parulidae	1.00
Cassin's Sparrow	Emberizidae	1.00	Lawrence's Warbler	Parulidae	1.00
Fox Sparrow	Emberizidae	1.00	Mourning Warbler	Parulidae	1.00
Harris' Sparrow	Emberizidae	1.00	Prairie Warbler	Parulidae	1.00
American Kestrel	Falconidae	50.00	Tennessee Warbler	Parulidae	1.00
Prairie Falcon	Falconidae	1.00	Western Palm Warbler	Parulidae	1.00
Pine Siskin	Fringillidae	1687.00	House Sparrow	Passeridae	60.00
Lesser Goldfinch	Fringillidae	397.00	Red-shafted Flicker	Picidae	52.00

(con.)

Table 1 (Con.)

Common name	Family	Captures
Downy Woodpecker	Picidae	22.00
Red-naped Sapsucker	Picidae	11.00
Hairy Woodpecker	Picidae	8.00
Ladder-backed Woodpecker	Picidae	6.00
Williamson's Sapsucker	Picidae	2.00
Northern Flicker	Picidae	1.00
Northern Flicker Intergrade	Picidae	1.00
Ruby-crowned Kinglet	Regulidae	787.00
Golden-crowned Kinglet	Regulidae	6.00
Verdin	Remizidae	6.00
White-breasted Nuthatch	Sittidae	24.00
Red-breasted Nuthatch	Sittidae	13.00
Burrowing Owl	Strigidae	8.00
Great Horned Owl	Strigidae	8.00
Western Screech-owl	Strigidae	7.00
Flammulated Owl	Strigidae	2.00
European Starling	Sturnidae	5.00
Blue-gray Gnatcatcher	Sylviidae	14.00
Western Tanager	Thraupidae	144.00
Summer Tanager	Thraupidae	118.00
Hepatic Tanager	Thraupidae	4.00
Scarlet Tanager	Thraupidae	1.00
Black-chinned Hummingbird	Trochilidae	4.00
Rufous Hummingbird	Trochilidae	1.00
Bewick's Wren	Troglodytidae	198.00
House Wren	Troglodytidae	161.00
Marsh Wren	Troglodytidae	11.00
Cactus Wren	Troglodytidae	2.00
Rock Wren	Troglodytidae	2.00
Carolina Wren	Troglodytidae	1.00
Winter Wren	Troglodytidae	1.00
American Robin	Turdidae	307.00
Hermit Thrush	Turdidae	259.00
Swainson's Thrush	Turdidae	12.00
Townsend's Solitaire	Turdidae	4.00
Dusky Flycatcher	Tyrannidae	436.00
Willow Flycatcher	Tyrannidae	255.00
Western Wood-Pewee	Tyrannidae	225.00
Western Flycatcher	Tyrannidae	77.00
Gray Flycatcher	Tyrannidae	73.00
Black Phoebe	Tyrannidae	67.00
Ash-throated Flycatcher	Tyrannidae	48.00
Western Kingbird	Tyrannidae	42.00
Hammond's Flycatcher	Tyrannidae	41.00
Say's Phoebe	Tyrannidae	12.00
Olive-sided Flycatcher	Tyrannidae	10.00
Brown-crested Flycatcher	Tyrannidae	5.00
Least Flycatcher	Tyrannidae	4.00
Common Barn-owl	Tytonidae	15.00
Warbling Vireo	Vireonidae	259.00
Solitary Vireo	Vireonidae	67.00
Gray Vireo	Vireonidae	2.00
Red-eyed Vireo	Vireonidae	2.00
Bell's Vireo	Vireonidae	1.00
Yellow-throated Vireo	Vireonidae	1.00

^aSee Kelly and Finch (this volume) for scientific names of bird species and for summaries of mist-netting standardized by number of netting hours.

setting. Urban development may narrow the corridor width available to migrants, causing them to concentrate as they funnel through a narrower band of vegetation at the Nature Center than at the Bosque del Apache. Annual fluctuations in numbers of juvenile birds also influenced overall numbers of captures.

Species Composition

A total of 272 species were detected using both mist-netting and point counts. Of those, 222 species were landbirds and the remainder were waterbirds and shorebirds. Of the landbirds, 98 species were neotropical migrants (44.4 percent); 107 species were short-distance migrants (48.2 percent); 6 were crossborder breeders (2.7 percent) and 11 species were year-round residents (5.0 percent). Many of the short-distance migrants were winter residents at our study sites.

Number of Species by Family

Of the 157 species of landbirds banded, 64 species (40.8 percent) and 22,400 individuals (84.9 percent) were common; 52 species (33.1 percent) and 4,100 individuals (15.6 percent) were uncommon and 41 species (26.1 percent) and 117 individuals (0.4 percent) were rare in New Mexico (table 1). The Family Parulidae (warblers) had the most species captured (32) followed by the family Emberizidae (sparrows, grosbeaks, blackbirds) with 26 species. The third most dominant family, Tyrannidae (flycatchers) had 13 species captured. Species with over 1,000 individuals captured were the Wilson's Warbler (*Wilsonia pusilla*), Chipping Sparrow (*Spizella passerina*), White-crowned Sparrow (*Zonotrichia leucophrys*), Pine Siskin (*Carduelis pinus*) and MacGillivray's Warbler (*Oporornis tolmiei*) (table 1). For capture rates of individual species standardized by constant mist-netting effort, see Kelly and Finch (1999 in this volume).

Timing of Migration

Spring migration occurred primarily during the middle of April through the end of May with a core period of 5 weeks. Average captures/day at each site showed little fluctuation by week within the core period (fig. 2). The mean number of captures at the Nature Center from 1994-1997 tended to be higher than at the Bosque del Apache in early spring. The peak period of spring migration was about a week later at the Nature Center which is 150 km north of the Bosque del Apache.

Fall migration was more prolonged than spring migration (fig. 2). Mean number of captures peaked during the first 2 weeks of September at both sites. The mean number of captures from 1994-1997 was lower in fall at the Bosque del Apache NWR than at the Rio Grande Nature Center. The Nature Center had small fields containing nutritional crops (sunflower and corn) that were located within and near the mist-netting study area. This may have influenced capture rates at the Nature Center by drawing more birds into the vicinity than at the Bosque del Apache.

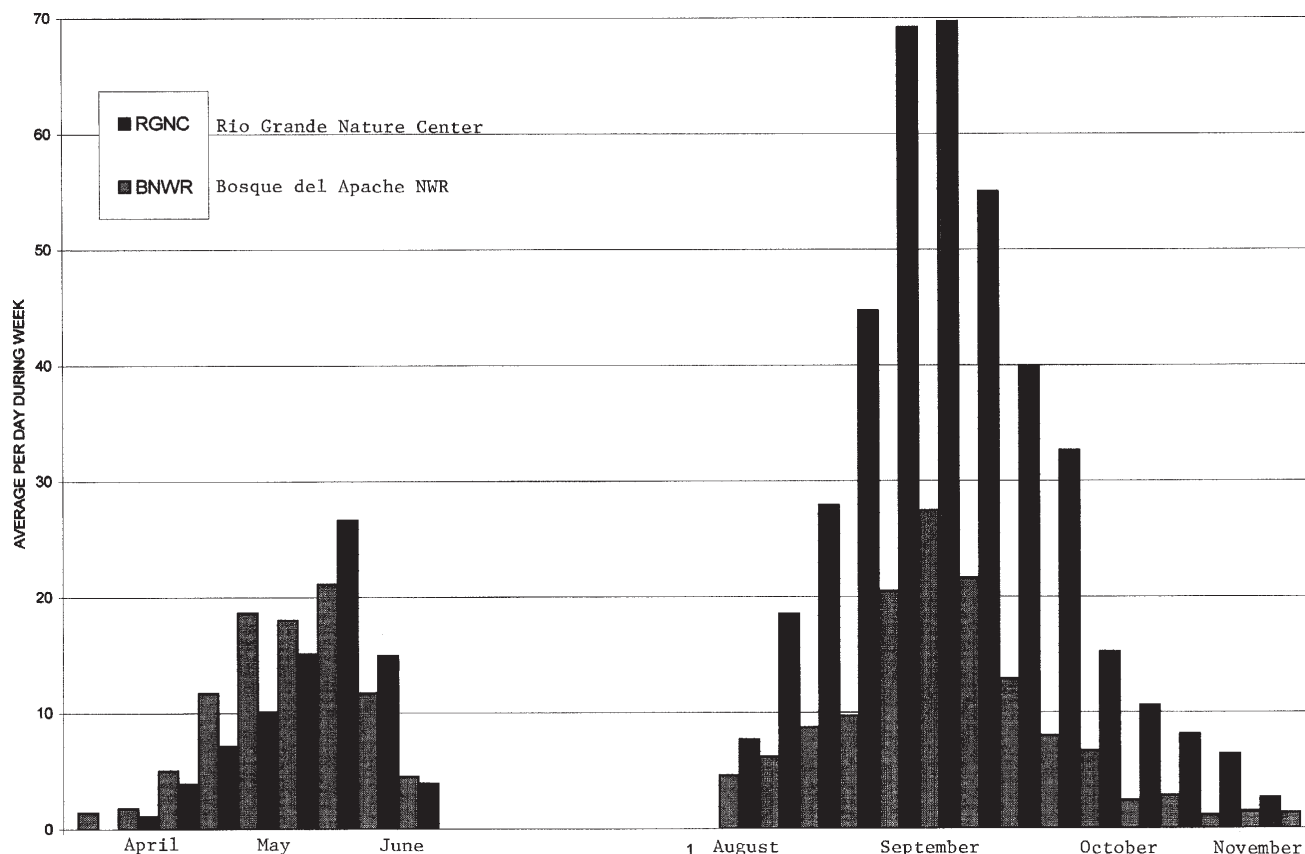


Figure 2—Weekly averages of Neotropical migrant bird captures at the Bosque del Apache NWR and the Rio Grande Nature Center Spring and Fall 1994-1997.

Habitat Use

Results of point counts in different dominant vegetation types suggested differential use of habitats by migrating species. More birds were detected in agricultural-edge habitats than in other habitats, particularly in the fall when the crops had matured. Second highest bird counts were in the two cottonwood habitat types (fig. 3). Birds were counted more frequently in willow habitat in spring than in fall.

Point count results differed from netting results in terms of species dominance patterns. We suggest that counts in open habitats (agricultural edge and cottonwood) may over-represent open-habitat species whereas counts in denser habitat (willow) may under-represent shrub bird species. For example, small, quiet passerines that stop in dense willow thickets during migration may not be readily heard or seen during point count sessions but may be detected through netting efforts. Also, birds and nets are more visible in open habitats than in closed habitats, and presumably therefore, more birds may be detected by sight in open habitats during point counts than at nets which, if easily seen, will be avoided.

Many migrants stayed at sites to breed. We have many records of individual birds returning year after year to the same areas to breed. Also, at the start of spring season and

the end of fall season, we encountered many birds that winter at the sites. Stopover times for most of the migrants were limited to one or two days except for the winter residents and resident breeders. Because stopover times were short and low numbers of neotropical migrants were recaptured, it is difficult to determine the underlying basis for stopover habitat selection (i.e., habitat structure, food supply, presence of water). Nevertheless, it was clear that certain species were observed or captured more often in some habitats than in others. For example, the Wilson's Warbler, a very abundant species, was most frequently caught or counted in willow habitats each year even though willow is less common at our sites than many other habitats, suggesting that Wilson's Warbler preferentially selected willow during stopover.

Habitats at our study sites have not been altered during our period of study except for willow which is periodically mowed along irrigation ditches and water conveyance channels (see Kelly and Finch 1999 in this volume). Given that willow habitat is used by many migrants, we suggest that managers evaluate their mowing designs to determine if mowing is really needed, and if so, whether the schedule or protocol can be modified to allow willows to grow high enough to enhance bird use.

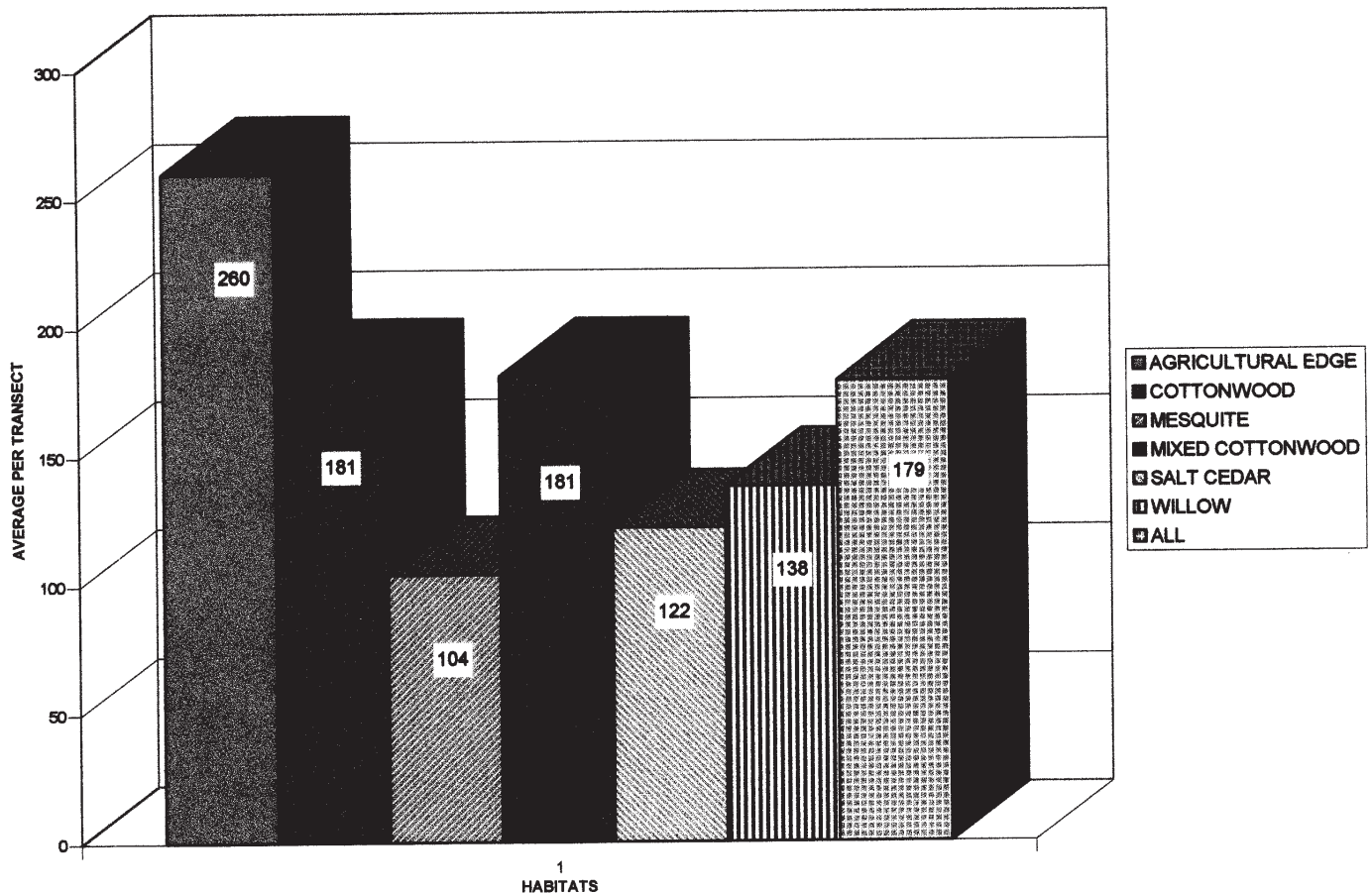


Figure 3—Use of habitats during spring and fall migration in the middle Rio Grande Riparian Corridor 1994-1997.

Acknowledgments

We thank Dr. Wang Yong and Dr. Jeff Kelly for their contributions to this study. David Hawksworth, Gus Bodner, and Susan Allerton have done a large amount of the technical field work associated with this study. Rio Grande Bird Research, Inc. (Nancy and Steve Cox) cooperated and shared their data on the Rio Grande Nature Center portion of this study. We are grateful to the Bosque del Apache National Wildlife Refuge, Rio Grande State Park, and the City of Albuquerque Open Spaces Division for their interest and support. This study was funded by the Bureau of Reclamation, the New Mexico Department of Game and Fish, and the Rocky Mountain Research Station.

References

- DeLay, L.; Finch, D.M.; Brantley, S.; Fagerlund, R.; Means, M.D.; Kelly, J.F. 1999. Arthropods of native and exotic vegetation and their association with Willow Flycatchers and Wilson's Warblers. (This volume.)
- Finch, D.M.; Wolters, G.L.; Yong, W.; and Mund, M.J. 1995. Plants, arthropods, and birds of the Rio Grande. Pp. 133-164 in D.M. Finch and J.A. Tainter (eds.), *Ecology, diversity, and sustainability of the Middle Rio Grande Basin*. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. General Technical Report RM-GTR-268.
- Finch, D.M.; Kelly, J.F. 1999. Status and migration of the Southwestern Willow Flycatcher in New Mexico. (This volume.)
- Finch, D.M.; Yong, W. 1996. Use of willow habitat along the Low-Flow Conveyance Channel by willow flycatchers and other migratory landbirds. 1996 Progress Report to the Bureau of Reclamation, Albuquerque, NM.
- Finch, D.M.; Yong, W. In press. Landbird migration in riparian habitats of the Middle Rio Grande: A Case Study. *Studies in Avian Biology*.
- Kelly, J.F.; Finch, D.M. 1999. Use of saltcedar vegetation by landbirds migrating through the Bosque del Apache National Wildlife Refuge. (This volume.)
- Kelly, J.F.; Finch, D.M.; Means, M.D. 1997. 1997 Annual report on bird migration along the Low-Flow Conveyance Channel in the Bosque del Apache NWR. Progress report to the Bureau of Reclamation, the NM Game and Fish Department, and the Bosque del Apache National Wildlife Refuge.
- Kelly, J.F.; Smith, R.; Finch, D.M.; Moore, F.R.; Yong, W. (in review). Influence of summer biogeography on wood warbler stopover abundance. *Condor*.
- Yong, W.; Finch, D.M. 1998. Age-related population trends of landbirds migrating through Southwestern semi-arid grassland. Pp. 81-93, in B. Tellman, D.M. Finch, C. Edminster, and R. Hamre, (eds.), *The Future of Arid Grasslands: Identifying Issues, Seeking Solutions*. USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-3.
- Yong, W.; Finch, D.M. 1997. Populations trends of migratory landbirds along the middle Rio Grande. *Southwestern Naturalist* 42:137-147
- Yong, W.; Finch, D.M.; Moore, F.R.; Kelly, J.F. (in press). Stopover ecology and habitat use of migratory Wilson's Warblers. *Auk*.

Status and Migration of the Southwestern Willow Flycatcher in New Mexico

Deborah M. Finch
Jeffrey F. Kelly

Abstract—In the Southwestern United States, recent degradation of riparian habitats has been linked to decline of the Southwestern subspecies of the Willow Flycatcher. During a 2-year banding effort, migration patterns and bird fat content were analyzed. Recommendations for managers, and outlines for conservation plans, are included.

The Willow Flycatcher (*Empidonax traillii*) is a neotropical migratory landbird that breeds throughout the United States and southern Canada and is fairly abundant in the northern portion of its range. The species winters in the Choco Lowland, Gulf-Caribbean Slope, and the Pacific Arid Slope zoogeographic regions of Latin America and South America (Stotz and others 1996), although the limits of its winter distribution are poorly known. Regional variation among breeding individuals has long been considered prominent enough to warrant subspecies designations (Phillips 1948). Currently, most experts recognize 4 or 5 subspecies of the Willow Flycatcher (Unitt 1987, Browning 1993).

Recent degradation of riparian habitats in the southwestern United States is believed to be linked to the decline of the southwestern subspecies of the Willow Flycatcher (*Empidonax traillii extimus*). The Southwestern Willow Flycatcher breeds in Arizona, New Mexico, southern California, and southern parts of Utah, Nevada, and Colorado. Owing to its small population size, the southwestern subspecies was listed as federally endangered in 1995 and critical habitat was designated in 1997. Although used for migration and breeding, none of habitat associated with the Rio Grande was included in the critical habitat designation. While the majority of the flycatcher monitoring programs focus on breeding surveys, nesting success, and cowbird parasitism, it is widely acknowledged that declines in the abundance of this species may also be attributable to poor quality habitats visited in winter or during migration stopover.

In the Southwestern U.S. riparian corridors attract a concentration of migrating songbirds including Willow Flycatchers. The Rio Grande is the second largest riparian system in the Southwest and maintains the largest

cottonwood forest in North America (Whitney 1994). This river system is also a primary source of agricultural and municipal water in both New Mexico and Texas. Cottonwood-willow habitats along the Rio Grande were historically associated with a braided river channel that meandered across a broad floodplain. The need to deliver water in a reliable manner and to limit damage due to flooding have resulted in management to reduce the meandering of the channel and the variability in river flow. Hence, riparian vegetation is restricted to the permanent watercourses that include the Rio Grande and associated water conveyance channels.

This paper gives a brief overview of Willow Flycatcher breeding status throughout the state of New Mexico and describes its migration pattern through the middle Rio Grande valley. We also summarize information on conservation plans underway.

Breeding Surveys 1994 to 1996

Breeding sites of the Southwestern Willow Flycatcher have been documented in New Mexico on the Upper Rio Grande and Rio Chama (Taos and Rio Arriba County), the Zuni River (McKinley County), the Middle and Lower Gila River (Grant County), the Middle Rio Grande (Valencia and Socorro Counties), and the Lower Rio Grande (Dona Ana County) (Williams 1997a). During flycatcher surveys from 1994 through 1996, at least 22 territories were found each year on the Upper Rio Grande (Tierra Azul, Taos Junction, Orilla Verde, Velarde, and San Juan Pueblo), 5 on the Chama, 17 on the Middle Rio Grande (Isleta, Peralta Dr., Bosque del Apache, San Marcial), 5 on the Zuni River, 5 on the Canadian River, 2 on the Lower Rio Grande (Radium Springs), and over 140 on the Gila River (Fort West Ditch, U-Bar Ranch, Redrock, Gila Lower Box). By 1998, the number of flycatcher territories jumped to over 220 (Dennis Parker and Scott Stoleson personal communications) owing to greater survey coverage in the Cliff-Gila Valley.

Number of known flycatcher sites, i.e., sites with at least one territory, varied by year, with 17 sites detected in 1994; 13 in 1995; and 19 in 1996 (Williams 1997a). Of these, 16 sites had breeding attempts in one or more years. In 1996, 18 sites had 1-4 territories, with breeding observed at 11 of them; 4 sites had 5-14 territories, with breeding at all of them; and only 1 site had greater than 15 territories. This latter site was on the U-Bar Ranch along the Gila River between Cliff and Gila.

The Rocky Mountain Research Station initiated a research study in 1997 on the U-Bar Ranch to determine flycatcher nesting success and rates of cowbird parasitism in different-sized patches of habitat. Based on 1997 results,

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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flycatchers selected box elder (*Acer negundo*) more frequently than other woody plants including willow to nest in and placed their nests higher on average than any other known *E. traillii* population in the United States (Scott Stoleson and Deborah Finch unpublished data). Box elder foliage is dense, and its twigs are structured in a way that was apparently highly suitable for nest placement by Gila River flycatchers. The Cliff-Gila breeding site had a high abundance of flying insects, moist soils, and numerous irrigation ditches criss-crossing the property. Larger habitat patches were closed to livestock during the breeding season. Brown-headed cowbirds (*Molothrus ater*) were present, but brood parasitism rates at flycatcher nests whose contents could be monitored were low (17 percent) relative to other hosts such as yellow-breasted chats (*Icteria virens*) and yellow warblers (*Vermivora celata*) (Stoleson and Finch unpublished data).

Lessons learned from studying the habitat conditions used by the Cliff-Gila population may be helpful for recovering the flycatcher and its habitats elsewhere in New Mexico, such as in the bosque of the middle Rio Grande. For example, the wet, "buggy" ditch habitats of densely-foliated, small-diametered shrubs or trees found on the U-Bar Ranch can potentially be simulated elsewhere. Similar conditions can be created through the manipulation of water in irrigation channels, alteration of channel mowing schedules, creation of backwater ponds, revegetation with native woody plants at suitable sites, and control of salt cedar (an alien plant that dries soils). To evaluate the potential of ditches to support flycatchers along the Rio Grande, let us turn to our migration study to determine if and how migrating Willow Flycatchers use channels during stopover.

Migration Study 1996 to 1997

Low Flow Conveyance Channel

To investigate the use of the Low Flow Conveyance Channel (LFCC) by Willow Flycatchers (*Empidonax traillii*) and other migrant songbirds, the Bureau of Reclamation (BOR) initiated a study in cooperation with the USDA-FS's Rocky Mountain Research Station in 1996. The objective of this study was to determine the effects of a rotational mowing system on the use of the Low Flow Conveyance Channel (LFCC) by migrant Willow Flycatchers and other songbirds. In the 1950's the LFCC was built to carry water from the Rio Grande at San Acacia to Elephant Butte Reservoir. This diversion was necessary because too little water was reaching Elephant Butte Reservoir and salt cedar had invaded the river channel and blocked flow in several sites. The LFCC was designed to carry 2,000 cubic feet per second (cfs) from the river to the reservoir with maximum hydraulic efficiency. Water has not been diverted into the LFCC since 1985 and currently the LFCC is used to capture irrigation return flows and as a shallow groundwater drain.

The vegetation along the LFCC's is comprised of primarily coyote willow (*Salix exigua*) and seep willow (*Baccharis* sp.). This vegetation was mowed annually from 1959 through 1994. As part of an agreement with the U.S. Fish and Wildlife Service the mowing of the LFCC was placed on a rotational schedule in 1996. Under this schedule 21 to 30 percent

of the LFCC will be mowed annually. This schedule will result in multiple age classes of willow vegetation that are potential habitat for migrant birds. For instance, in our study area vegetation has grown rapidly and resulted in dense stands of 6-15 ft tall vegetation that was 8-25 ft wide. While these willow stands have not been historically available to migrating birds like Willow Flycatchers they may represent an important resource for this endangered subspecies.

Study Site and Mist Net Operation

In both 1996 and 1997 field data were collected in the first week of April through the first week of June and from the first week of August through the first week of November. In 1996 and 1997 nets were operated in willow, agricultural edge, cottonwood bosque and along the LFCC. Standard nylon mist nests (12 m x 2.6 m) were used. Mist nets were operated 5 days a week. Unless rain, high winds, or temperature dictated a change, mist nets were opened 15 minutes before sunrise and operated approximately six hours each banding morning. Each captured individual was weighed to the nearest 0.1 g using a digital electronic balance. We estimated fat stores of each bird by observing the subcutaneous fat deposits in the interclavicular fossa and abdomen according to a six-point scale developed by Helms and Drury (1960). Unflattened wing chord, tarsus, tail length relative flight feather length (for wing formula calculation), presence of notch and emargination of primaries, bill width, bill length, lower mandible color, wingspan, and tail shape were measured according to Svensson (1984) and Pyle (1997). The amount of skull ossification was examined in fall to identify age. Plumage color and relative contrasts between body parts were recorded by referring to the color standard of Smithe (1975). Each bird was banded with a numbered aluminum leg band.

The same 14 net sites along the LFCC were used in 1996 and 1997. These net sites were located on the west bank of the LFCC, immediately south of the North Bosque del Apache National Wildlife Refuge Check Structure. We selected this location for the following reasons: 1) the willow growth in this section was typical of the LFCC, i.e., data collected from the area would be relatively representative of the entire LFCC; 2) the area was close to our original study site, therefore, this data set could be used as a spatial control for comparisons and it also made it possible to operate both net site concurrently. 3) the site was inside the Refuge boundary and, therefore, the probability of nets being vandalized was reduced. To maximize capture rate, nets were set up approximately perpendicular to the LFCC at 30-50 m intervals.

In addition, the 5 net sites established in salt cedar habitat adjacent to the LFCC in 1996 were also operated in 1997, and 2 additional nets were operated in this habitat bringing the total to 7. Of the 14 nets operated in the cottonwood habitat in 1996, 7 were operated in 1997. The number of nets in the willow habitat was increased from 3 in 1996 to 4 in 1997. Netting effort remained constant at 3 nets in the agricultural edge habitat. In total 39 nets were operated in during 1996 and 35 nets were operated in 1997. Because some of our net sites changed between 1996 and

1997 we needed to standardize our capture data to make comparisons. For this purpose we calculated our banding effort in each season in terms of net-hours. A single mist net operated for one hour is a net-hour.

Willow Flycatcher Identification

Willow Flycatchers are difficult to distinguish from Alder Flycatchers (*Empidonax alnorum*) in the field (Stein 1963, Pyle 1997). Most individuals (90 percent) of these species can however be separated based on Steins formula, which combines several wing measurements and bill length (Stein 1963). Alder flycatchers have not previously been recorded in New Mexico (Williams 1997b), but to demonstrate that the birds that we captured were Willow Flycatchers rather than Alder Flycatchers we undertook this analysis. We also identified Willow Flycatchers to subspecies in the field. These identifications were based on a number of morphological and coloration measurements. Because there is no proven method of validating these subspecies identifications, they should be applied with caution (Yong and Finch 1997). It is unlikely that every individual was classified correctly and the total accuracy cannot be estimated. Here we report some analyses designed to uncover potential distinctions among subspecies. We distinguished four subspecies (Browning 1993): *Empidonax traillii adastus*, *E. t. brewsteri*, *E. t. traillii*, and the Southwestern form *E. t. extimus*. For most of this report we distinguish only those birds categorized as endangered Southwestern Willow Flycatchers and lump those of other subspecies.

Banding Effort

In 1996 we netted for 7,997 net hours in the spring and 13,085 net hours in the fall for a total of 21,092 net hours. The majority of this effort was concentrated on the LFCC (2,491 net-hours in spring and 4,673 net hours in fall) and in cottonwood bosque (3,217 hrs in spring and 4,698 net hours in fall). Our overall netting effort in 1997 was very similar to that in 1996. We netted for 7,691 net hours in the spring and 12,938 net hours in the fall for a total of 20,629 net hours in 1997 which is 98 percent of our 1996 effort. A larger majority of our 1997 effort was focused on the LFCC (8,183 net hrs; 40

percent of total effort). Cottonwood and salt cedar habitats were the next most intensely banded sites with about 4,151 net hours each.

Results of Migration Study

Analysis by Stein's formula indicated that 88.5 percent of the birds that we have identified as Willow Flycatchers can be confirmed as Willow Flycatchers rather than Alder Flycatchers. Several factors indicate that birds whose species could not be confirmed on the basis of Stein's formula were also Willow Flycatchers. First, this formula only separates 90 percent of birds known to be Willow Flycatchers (Stein 1963). Thus a pure sample of Willow Flycatchers would not have more separation than our sample. Second, the presence of an Alder Flycatcher has never been confirmed in New Mexico (Williams 1997b). Third, young Willow Flycatchers have been shown to be less distinguishable from Alder Flycatchers on the basis of Steins formula (Hussell 1991). For these reasons we are confident that our identification of these birds as Willow Flycatchers is accurate.

A total of 92 Willow Flycatchers have been captured in the 2 years of the study and 13 of these were categorized as belonging to the endangered Southwestern subspecies. A total of 41 Willow Flycatchers were caught along the LFCC of which 5 were categorized as southwestern subspecies. It appears that the primary characteristic that we used to categorize flycatchers to subspecies was back color (table 1).

Principal Components analysis of tail length, wing length, bill length, wing formula, tarsus length (table 2) did not reveal a single or combination of morphological features that readily distinguishes among the subspecies of Willow Flycatchers. Thus, the accuracy with which subspecies assessment can be made in the field remains unclear.

Because of the low number of captures of Southwestern Willow Flycatchers it is impossible for us to make any generalizations about habitat use of this subspecies that are distinct from the rest of the species. As was true for most species, the capture rate of Willow Flycatchers declined from 1996 (2.4 birds/100 net hours) to 1997 (2.0 flycatchers/100 net hours). The greatest number of Willow Flycatchers were consistently captured in the LFCC habitat although capture rates were higher in the willow habitat (fig. 1).

Table 1 — Back colors of 77 Willow Flycatchers caught while migrating along the Middle Rio Grande between 1994 and 1996. Color numbers and descriptions refer to those in the Naturalist's Color Guide (Smythe 1975). Individuals were assigned to color categories by matching the color of their back feathers to the most similar color sample. Individuals were assigned to subspecies in the field. Numbers in parentheses are the percent of individuals in each color category that were assigned to each subspecies.

Color Number	Description	Subspecies			
		<i>Adastus</i>	<i>Brewsteri</i>	<i>Extimus</i>	<i>Traillii</i>
29	Brownish Olive	2 (18)	1 (2)	0	0
43	Grayish Olive	1 (9)	2 (4)	19 (100)	2 (100)
46	Olive Green	1 (9)	0 (0)	0	0
47	Olive Green	0	1 (2)	0	0
48	Olive Green	1 (9)	40 (89)	0	0
49	Greenish Olive	6 (54)	1 (2)	0	0

Table 2—Mean (sd) mass and wing, tail, and tarsus, lengths of Willow Flycatchers caught in the Bosque del Apache in 1996 and 1997. N is number of birds measured.

			Mass (g)		Wing (cm)		Tail (cm)		Tarsus (cm)	
			$\bar{x}$	(sd) n	$\bar{x}$	(sd) n	$\bar{x}$	(sd) n	$\bar{x}$	(sd) n
1996.00	FA	AG	13.0 (—)	1	66.0 (—)	1	56.0 (—)	1	18.5 (—)	1
		CO	— (—)	0	66.5 (0.7)	2	55.5 (0.7)	2	16.5 (0.8)	2
		LF	11.4 (1.0)	8	66.7 (3.4)	8	54.4 (4.2)	8	15.4 (1.3)	8
		SS	12.6 (0.8)	7	65.9 (2.0)	7	55.7 (2.0)	6	16.2 (1.4)	7
	SP	SW	12.1 (0.6)	4	67.2 (1.8)	5	53.8 (2.4)	5	16.6 (1.0)	5
		AG	11.9 (0.4)	2	68.2 (2.5)	2	58.5 (2.1)	2	16.0 (0.3)	
		CO	— (—)	0	— (—)	0	— (—)	0	— (—)	0
		LF	12.1 (0.8)	12	67.3 (3.1)	13	56.7 (1.8)	13	16.4 (0.7)	13
		SS	12.9 (—)	1	68.0 (—)	1	59.0 (—)	1	16.8 (—)	1
		SW	12.1 (1.0)	11	68.1 (3.3)	11	58.1 (2.8)	11	16.5 (0.9)	11
1997.00	FA	AG	14.2 (—)	1	70.0 (—)	1	58.0 (—)	1	16.6 (—)	
		CO	— (—)	0	— (—)	0	— (—)	0	— (—)	0
		LF	11.3 (0.8)	7	66.1 (2.6)	7	55.6 (3.2)	7	15.5 (1.7)	7
		SS	12.3 (0.5)	2	65.0 (4.2)	2	55.0 (2.8)	2	15.5 (0.2)	2
	SP	SW	11.5 (0.2)	3	65.3 (3.1)	3	53.3 (2.9)	3	16.0 (0.2)	3
		AG	— (—)	0	— (—)	0	— (—)	0	— (—)	0
		CO	12.1 (1.5)	4	72.6 (3.0)	4	61.3 (3.9)	4	16.8 (0.6)	4
		LF	12.8 (0.9)	13	69.5 (3.3)	13	57.2 (3.5)	13	16.5 (0.8)	13
		SS	12.4 (0.6)	6	69.0 (2.5)	7	59.4 (3.1)	7	16.4 (1.1)	7
		SW	13.5 (1.2)	5	69.4 (2.9)	5	57.8 (2.6)	5	16.6 (0.8)	5

To assess the relative habitat use of Willow Flycatchers we compared the percent of birds captured in each habitat to the percent of banding effort (net hours) devoted to each habitat. In each season except fall 1996 a larger percentage of Willow Flycatchers were captured along the LFCC than the percent effort devoted to that habitat. This indicates that Willow Flycatchers were relatively abundant in this habitat. This pattern was also evident in the willow habitats in all seasons and the salt cedar habitat in the fall of 1996 and the spring of 1997. Both the agricultural edge and the cottonwood habitats consistently captured fewer Willow Flycatchers than the amount of effort expended (fig. 1).

Willow Flycatcher migration peaked in the 1st week of June during the spring and in the 1st week of August in the fall (fig. 2). The peak of migration appears to be more narrow in the spring than in the fall. There does not appear to be a clear difference among habitats in the timing of migration. The majority of birds had little fat as indicated by fat scores of zero or one (fig. 3). Again there were no obvious differences in fat scores among birds captured in different habitats. This lack of pattern also was apparent in the mass of birds captured in different habitats (table 2).

Recommendations for the Future

It is clear from our data that Willow Flycatchers are using the LFCC as a stopover habitat during both the spring and the fall. By intensely studying an area of the LFCC we have been able to document both yearly variation in habitat use and the progression of change that follows rest from mowing. The fairly well developed willow stands that have developed in the absence of mowing since 1995 indicates that a rotational mowing system may be a viable means for

providing habitat for migrant birds while not compromising the function of the LFCC. To understand the compatibility of these uses at a broad scale, however, it is necessary to have a broad view of the conditions that exist on the LFCC. That is, our study has been useful in documenting the potential to use rotational mowing to benefit migrant birds, but to understand how much of that potential can be realized we need to sample a broader portion of the LFCC.

To achieve this broader view of the LFCC we propose to continue our study of the same area that we have investigated over the past 2 years, but with reduced effort (3 days per week). On the remaining 2 sampling days per week we will measure vegetation and establish temporary netting sites at a spectrum of sites along the LFCC. This approach will give us a broader sample of vegetative structures, mowing histories and bird use data from which we can infer the relationship between mowing schedule and bird use along the LFCC. At the same time by maintaining some effort at the sites we have sampled previously we will be able to compare bird capture, vegetation, and arthropod abundance data collected in 1998 with that collected in previous years.

Conservation Plans and Research Needs

In January 1998, the U.S. Fish and Wildlife Service assembled a Recovery Team for the Southwestern Willow Flycatcher that is comprised of a technical subgroup and seven stakeholder implementation subgroups. The technical subgroup is made up of technical experts from universities, research institutions, agencies, and other organizations. Implementations teams are composed of stakeholders from special interest groups, conservation organizations, state and federal agencies, and other entities having a stake

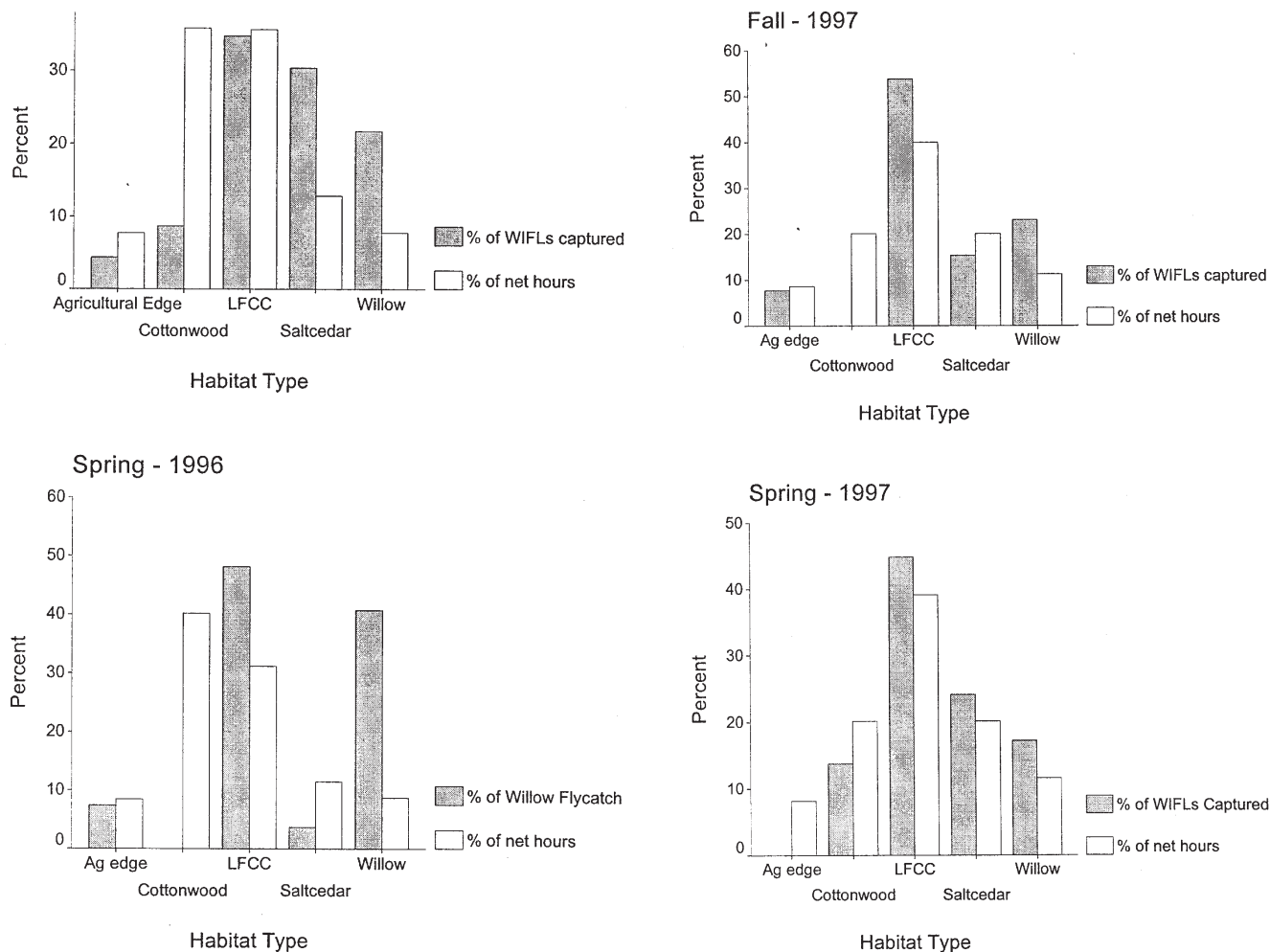


Figure 1—Percent of Willow Flycatchers and banding effort in each of 5 habitat of the Bosque del Apache. Relative abundance of flycatchers among habitats can be assessed by comparing the percent effort with the percent of captures within and among habitats. Habitats in which the percent captures bars are larger than the percent effort bars likely have higher abundances of flycatchers.

in, or affected by management of, the Willow Flycatcher and its habitats. A first draft of the recovery plan will be submitted to the Fish and Wildlife Service by October 1999.

A Conservation Assessment prepared by technical experts (many of whom are now on the Recovery Team) was financed by the U.S. Forest Service in 1997-98 and will be published or in press in a technical monograph series by 1999. The goal of this assessment is to review and synthesize the state of knowledge about the flycatcher and formulate recommendations for managing its populations and habitats throughout the Southwest. Designed to support the recovery plan, the review is composed of chapters on southwestern riparian history, flycatcher status, threats, winter and migration biology, breeding ecology, demography, effects of cowbird parasitism, flycatcher habitat use, management recommendations, and research needs. Some of the relevant management recommendations in the conservation assessment include:

- Close occupied sites to recreational use during the breeding season.

- Remove cows from occupied sites during the breeding season.
- Trap cowbirds at sites having parasitism rates that exceed 10 percent.
- Discourage spread of exotic woody plants such as salt cedar.
- Prevent wildfires in riparian areas and develop fire plans in advance of wildfires.
- Develop and conserve water for stimulating riparian vegetation growth.
- Reduce “phreatophyte” control on irrigation ditches and channels.
- Restore riparian areas near source populations of Willow Flycatchers.

The conservation assessment has also identified critical gaps in knowledge that prevent experts and managers from being fully effective in designing approaches for

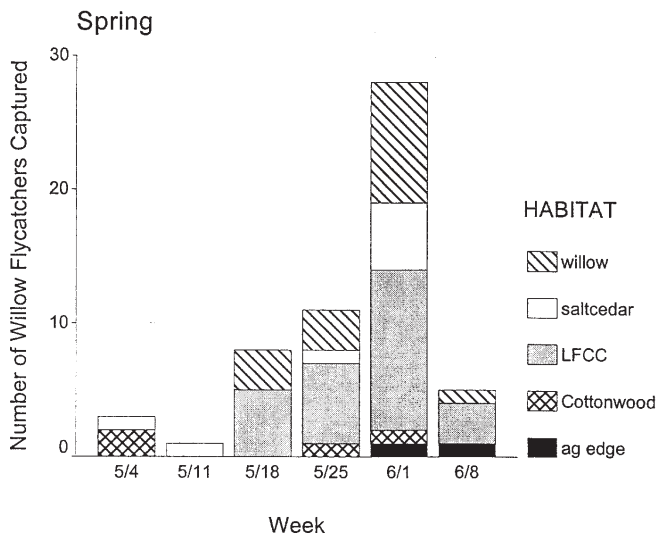
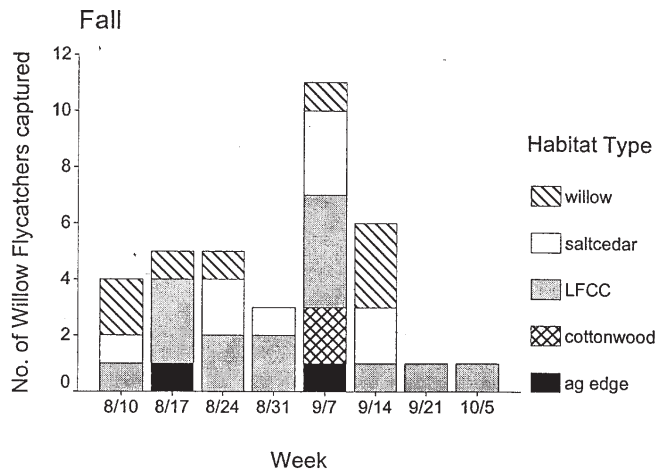


Figure 2—Number of Willow Flycatchers caught in the Bosque del Apache during the spring and fall by week and habitat.

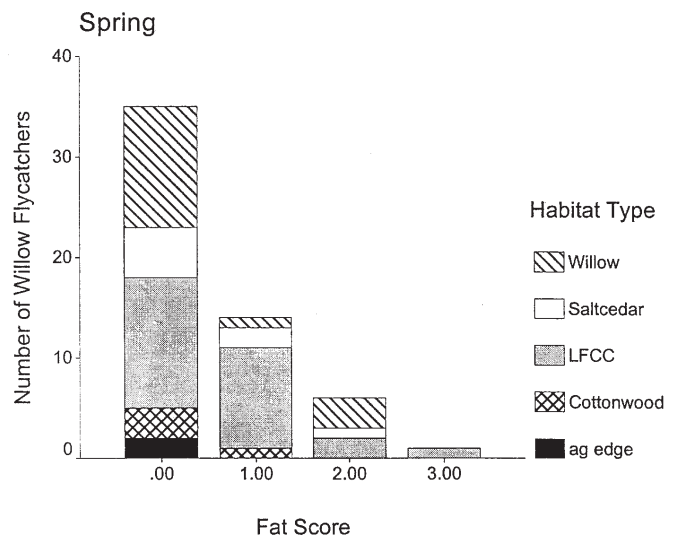
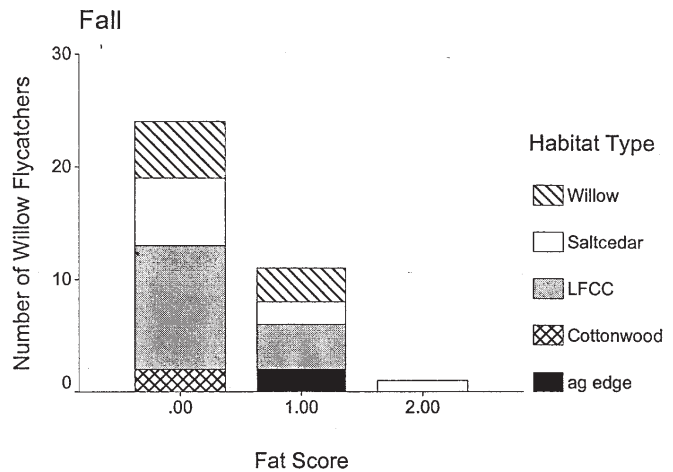


Figure 3—Fat scores of Willow Flycatchers caught in the Bosque del Apache in the spring and fall by habitat.

recovering flycatcher populations and habitats. Research needs include:

- Understanding the relationships between landscape attributes, habitat occupancy patterns and nesting success of the Southwestern Willow Flycatcher.
- Understanding how cowbird travel distances and parasitism rates pertain to livestock presence and absence, and Willow Flycatcher nesting sites.
- Developing knowledge of the direct effects of land use (grazing, ditching, recreation, exotic plant control, channel mowing, water management) on Willow Flycatchers.
- Evaluating flycatcher nesting success and migration stopover use in exotic and native vegetation.
- Designing and modifying methods to restore and sustain riparian habitats and recover flycatcher populations.

Conclusions

In summary, survey data indicated that the majority of Southwestern Willow Flycatchers breeding in New Mexico are found in the southwestern portion of the state, mostly on private property along the Gila River. In 1998, more than 200 territories were detected on the U-Bar Ranch alone in the valley between the towns of Cliff and Gila. Several breeding sites were also located on the Rio Grande but only two (San Juan Pueblo and San Marcial) had more than 5 flycatcher territories in 1995 and 1996. To recover flycatchers, more attention to habitat restoration along the middle and upper Rio Grande and associated tributaries is needed. Linking research knowledge of flycatcher habitat use in the Cliff-Gila valley to ongoing and new restoration efforts along the Rio Grande may be of benefit to recovering the flycatcher in the middle and northern regions of New Mexico. In addition, our study of flycatcher migration along

the Low Flow Conveyance Channel suggests that ditches and channels are important stopover habitat, particularly if water is present and bankside willows are allowed to grow. Based on our evaluation of stopover habitat use and Gila River breeding habitat use, we suggest that habitats for breeding Willow Flycatchers can be created along the Rio Grande if specific habitat conditions are supplied. These conditions include at minimum slow or still water, vegetation that supplies a suitable twig structure for nest placement (for example shrub willow, box elder), moist soils (unlikely where large salt cedar thickets have established), and a high abundance of flying insects.

Aknowledgments

We thank the Bureau of Reclamation in Albuquerque, the Bosque del Apache Wildlife Refuge, the Center for Field Research, and New Mexico Game and Fish Department for financial assistance, field grants, housing, and site access for conducting our bird migration study. We are grateful to the many field assistants, Earthwatch volunteers and volunteer interns who have helped us with this study. In particular, we thank Mike Means, Dave Hawksworth and Gus Bodner, for their dedication and length of service to the study.

References

- Browning, M.R. 1993. Comments on the taxonomy of *Empidonax traillii* (Willow Flycatcher) Western Birds 24:241-257.
- Helms, C.W. and W.H. Drury. 1960. Winter and migratory weight and fat: field studies on some North American buntings. Bird Banding 31:1-40
- Hussell, D.J.T. 1991. Spring Migrations of Alder and Willow Flycatchers in southern Ontario. J. Field Ornithology 62:69-77.
- Phillips, A.R. 1948. Geographic variation in *Empidonax traillii*. Auk 65:507-514.
- Pyle, P. 1997. Identification Guide to North American birds. Slate Creek Press.
- Stein, R.C. 1963. Isolating mechanisms between populations of Traill's Flycatcher. Proc. Am. Phil. Soc. 107:21-50.
- Smithe, F.B. 1975. Naturalists color guide. Am. Mus. Nat. Hist. New York.
- Svensson, L. 1984. Identification guide to European passerines. L. Svensson, Stockholm.
- Stotz, D.F., J.W. Fitzpatrick, T.A. Parker, and D.K. Moskovits. 1996. Neotropical birds: ecology and conservation. Univ. Of Chicago Press.
- Unitt, P. 1987. *Empidonax traillii extimus*: and endangered subspecies. Western Birds 18:137- 162/
- Whitney, J.C. 1996. The Middle Rio Grande: Its ecology and management. Pages 4-21 In (D. Shaw and D.M. Finch tech. eds.) Desired future conditions for southwest riparian ecosystems: bringing interests and concerns together. General Technical Report RM-GTR-272. Rocky Mountain Research Station, Fort Collins, CO.
- Williams, S. O., III. 1997a. Surveys of Southwestern Willow Flycatcher, 1995-1996. NM Game and Fish Report to U.S. Fish and Wildlife Service, Albuquerque, NM.
- Williams, S. O., III. 1997b. Checklist of New Mexico bird species. NMOS Bulletin 25:51-66.
- Yong, W. and D.M. Finch. 1997. Migration of the Willow Flycatcher along the Middle Rio Grande. Wilson Bulletin 109:253-268.

Biological Diversity in Montane Riparian Ecosystems: the Case of the Mexican Spotted Owl

Peter B. Stacey
Angela Hodgson

Abstract—Although usually considered to be a bird of old growth mixed conifer forests, the Mexican spotted owl historically occurred in a wide range of habitats from lowland cottonwood bosques to montane canyon systems. In a recent study of habitat use in central New Mexico, we found that owls roost primarily in canyon bottoms, and that they select sites that are characterized by deciduous trees and high structural complexity of vegetation, rather than by large diameter conifer trees per se. Intact riparian areas in montane canyons typically have considerable structure, yet, as in the lowlands, these habitats have undergone extensive modification and reduction. The unexpected diversity of habitat use of the Mexican spotted owl suggests that historic changes in upland riparian systems in the Rio Grande Basin may have impacted more species than originally believed.

Although the Mexican spotted owl (*Strix occidentalis lucida*) is often considered to be a species that depends primarily upon mature mixed-conifer forest, it actually is known to have historically nested in a surprisingly large range of habitats. For example, spotted owls once occurred in the lowland cottonwood bosques of New Mexico and Arizona (Bailey 1928, Phillips and others 1964), and even today they can still be found in some Arizona cypress and Maderan oak forests in SE Arizona (USDI Fish and Wildlife Service 1995). At the present time, however, most spotted owls in the Rio Grande Basin and throughout the southwest are restricted to canyon habitats at higher elevations in the mountains. The topography of these mountain systems can be extremely complex, and exposure, soil types and moisture regimes often vary over extremely short spatial scales. As a result, the vegetation communities within a particular owl territory may actually consist of a complex mosaic of plant associations that range from mixed conifer forests (usually dominated by Douglas-fir, *Pseudotsuga menziesii*, and southwestern white pine, *Pinus strobiformis*) on north facing slopes, ponderosa pine (*P. ponderosa*) forests on east and west facing slopes, and pinyon-juniper (*P. edulis* and *Juniperus* spp.) forests or scrub oak (*Quercus*) thickets on south facing slopes. In the canyon bottoms themselves, vegetation may range in some locations from relative intact

riparian forests dominated by narrow-leaf cottonwood (*Populus angustifolia*) and oak (primarily Gambel oak, *Quercus gambelii* and gray oak, *Q. grisea*), to open pine-oak meadows in areas that have been heavily impacted by livestock grazing (for a detailed description of these associations, see Dick Peddie 1993). Because of the floristic complexity that exists within most spotted owl territories in the southwest, it has not always clear which plant associations within the mosaic are actually important to the birds, and therefore which types of habitat modification may be most likely to adversely affect their continued survival.

Because the spotted owl has played a central role in controversies over timber harvests on public lands in the southwest and elsewhere, most previous studies of habitat selection in this subspecies have focused upon their association with large and/or commercially important conifer trees (Ganey and Balda 1994, Zwank and others 1994, Seamans and Gutierrez 1995). These studies found that spotted owls tend to roost or nest in areas that have more or larger diameter conifer trees than when compared to randomly chosen sites, and that they tend to use unmanaged conifer forests more often than would be expected by chance alone. However, these studies did not specifically examine the importance of other species such as the deciduous oaks and cottonwoods that often occur in the understory of canyon bottoms, although most authors have noted that oaks are common at many roost sites (see also Ganey and others 1992). Rinkevich and Gutierrez (1997) found that in Zion National Park in Utah, Mexican spotted owls are found only in canyon bottom habitats with well-developed riparian vegetation, and that they are absent from the pure mixed conifer forests on the plateaus at the tops of the cliffs. Similarly, there are no established nesting territories of spotted owls in the extensive mixed conifer forests on the Kiabab Plateau in northern Arizona, even though there are a number of birds in the canyons that radiate from the plateau (J. Goodman, pers. comm.; R. Silver, pers. comm.). These observations, when combined with the historical records of owls nesting in lowland riparian forests in the complete absence of mixed-conifer, suggest that tree species or vegetative characteristics other than, or in addition to, large diameter conifer trees, may be important in habitat selection in this subspecies.

The goal of this project was to explore this question for spotted owls that occur in montane canyon habitats in the middle Rio Grande basin of west-central New Mexico. Although we used the same general methods to study habitat selection as most prior studies (Ganey and Balda 1994, Zwank and others 1994, Seamans and Gutierrez 1995), we expanded our analysis in several ways. First, we included

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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both conifer and deciduous trees when sampling vegetation composition and structure in the roosting and randomly selected plots. Second, we recorded the presence in our plots of smaller diameter trees (>5 cm D.B.H.) than were included in previous studies (usually >10 cm D.B.H.), since many deciduous trees, particularly oaks, have small stem diameters and would otherwise be excluded from our analysis. And finally, in recognition of the high degree of spatial heterogeneity in the vegetation of owl territories, we undertook two different statistical comparisons. First, as was done in previous studies, we compared occupied owl roost sites with randomly chosen sites that were located within all of the different plant community types within the owls' territories (for example, pinon-juniper, ponderosa pine, deciduous/riparian, etc.). However, since we found that the owls did not actually use all of these associations for roosting, we conducted a second analysis in which we restricted the comparison of roost sites to only the subset of random plots that were located within the same vegetation associations used by the owls (mixed conifer/deciduous and mixed conifer; see below). The first comparison will reveal the general types of habitats or plant associations that the owl uses for roosting, while the second analysis examines the *specific characteristics of the vegetation* that appear to be important for habitat selection within that particular association(s). This second analysis is particularly useful in management, because it can give detailed information on the important habitat characteristics of the associations that are actually used by the owls, and therefore might be affected by different management activities within those associations.

Methods

Study Areas

The data reported here were collected as part of a long-term study of the Mexican spotted owl in west central New Mexico (Arsenault and others 1997, Kuntz and Stacey 1997). Our primary location for the roost-site analysis was located in the West Red canyon area of the San Mateo Mountains, 40 km west of the Rio Grande near Truth or Consequences, NM. Owls have been recorded in this canyon since at least the early 1900's (Ligon 1926) and we believe it represents habitats typical of those now occupied by this species in many of the mountain ranges in the southwest. The topography is characterized by deep forested canyons that extend from a central ridge of peaks that runs north-south along the length of the mountain chain. Elevations at the study site vary from 1800-3200 m, and the vegetation is a mix of scrub oak, pinyon-juniper, ponderosa pine, mixed conifer, and limited aspen and spruce-fir at the highest elevations (see Dick-Peddie 1993). Remnant riparian vegetation, consisting primarily of Gambel oak and scattered mature narrow-leaf cottonwood trees, occurs along all canyon bottoms. At the present time, there is little or no regeneration of the cottonwoods and most have died off. However, dense stands of cottonwood, willows (*Salix* spp.) and other riparian species can be found within livestock exclosures in West Red and elsewhere in the San Mateo Mountains, and we believe this to be the original vegetation association in the canyon

bottoms. But because the current vegetation has been extensively altered from its original condition, we refer to this association as "mixed-conifer/deciduous", since it is now dominated by conifers and oak trees, with mature cottonwoods in some locations. Most of the pure ponderosa pine and mixed-conifer forests in the San Mateos have been logged at least once during the past 50-100 years, although there is no timber harvest at present. The current land uses are primary livestock grazing (both summer and fall seasons) and recreation.

Detailed observations were made within three adjacent owl territories in the West Red Canyon watershed with a combined area of approximately 36 km². Additional qualitative assessments of owl roost areas were made in three other mountain ranges in west-central New Mexico, including the Black Range, the Magdalena Mountains and the Zuni Mountains. Vegetation in these ranges was similar to that of the San Mateo Mountains.

Habitat Analysis

We examined roosting habitat use from May through November, 1993-94. Spotted owls were first located during night surveys using standard techniques (Foresman 1983) and roost locations then determined the following day. We captured adult and juveniles at the roost using either a Balchatri trap or a 3.4 m noose pole. Each bird was then banded with an US Fish and Wildlife Service aluminum leg band and one color band. A 5 or 7.5-gram radio transmitter (Holohil Systems, Ltd., Woodlawn, Ontario, Canada) was then mounted on a central tail feather. The radio-tagged owls were then located 2-3 times per week while roosting, using a TRX 1000S radio telemetry receiver and a three-element Yagi antenna (Wildlife Materials, Inc., Carbondale, IL). The telemetry data were used to map the owls' breeding season home ranges using the minimum convex polygon method and the computer program CalHome (California Department of Fish and Game, Sacramento, CA). We marked the location of all roost locations, and all habitat measurements were taken at a later time when owls were not present. Roost sites within 50 meters of each other were considered part of the same cluster, even if they were used in different years. We did not include in the analysis any roost sites that were within 50 m of active nests, since spotted owls do not make their own nests, and instead must use either natural platforms in trees or caves, or the abandoned stick nests of other species. Since this could limit habitat choice, we examined roost locations of only non-breeding owls, or of family groups that had moved at least 100 meters from their nests.

We examined microhabitat characteristics within 0.04 ha circular plots at 64 breeding season (1 March-15 October) roost sites of radio-tagged owls and 69 random sites in the West Red Canyon study area. All random plots were located within the breeding season home ranges of the owls as determined by the radio-tracking. We used a random number table to generate UTM coordinates and then located the plot in the field using a Trimble global positioning system (Trimble Navigation, Sunnyvale, CA) with an accuracy of approximately 10-15 meters. Sample plots were centered on the roost tree or on the potential roost tree closest to the

center of each random plot. The number of sites measured was limited by time constraints and was not determined by statistical methods.

We measured 27 variables within each plot. A complete description of each variable and additional details of sampling methods is given in Hodgson and Stacey (1996). We recorded the species identity, height, and diameter at breast height (D.B.H.) for each tree > 5 cm D.B.H. within each plot using a D.B.H. tape and clinometer. We then calculated the basal area (m^2/ha) and density (trees/ha) for each species, and height and diameter classes of trees. We used a compass to measure the aspect at the center of the plot and placed each plot in one of eight directional categories. Canopy closure was measured as the average of four densitometer readings taken 5 meters from the center of the plot in each of the four cardinal directions, as well as the position of the plot along the slope (upper 1/3, middle 1/3, lower 1/3 of slope, or drainage bottom) and height of the owl roost. Each plot was also assigned to one of four forest general types: mixed-conifer, ponderosa pine woodland, pinyon/juniper woodland, or mixed-conifer/deciduous, as defined above. Juniper, pinyon pine and shrub live oak are the characteristic species of the pinyon/juniper woodland in this area, and we combined density and basal area of these species and designated the total as pinyon/juniper basal area and density.

Statistical Analysis

Means ($\pm$ SD) were calculated reported for all habitat variables. Most variables were not normally distributed and could not be normalized using standard transformations. To determine if there was non-random selection for habitat characteristics associated with roost sites, we compared random and roost plot variables using the non-parametric Mann-Whitney U test (SAS 1988). Since there was a total of 45 individual variables that could be tested with the same data set (Hodgson and Stacey 1996), the significance level for each test was conservatively set at $p \leq 0.005$, using the Bonferroni correction for 50 tests (Manly 1992). We analyzed the categorical variables, direction, position and forest type using Chi-square goodness-of-fit tests (SAS 1988).

Two different analyses were performed. First, to examine habitat selection within the entire range of vegetation associations present within the owls' home ranges, we compared roost sites to all of the random plots. Second, to determine if there was also non-random selection of roost sites within used forest types, the statistical influence of random plots in unused forest types (see Results) was removed by eliminating all plots that were in ponderosa pine or pinyon/juniper habitats from the random plot data set, since owls were never actually observed roosting in these forest types. All statistical analyses were then repeated using the subset of random plots that were located within mixed-conifer or mixed-conifer/deciduous oak ($n = 36$).

Results

Roost Locations

As part of our overall study, we located roosting sites between 1993 and 1995 in 30 different spotted owl territories in four mountain ranges in addition to the three primary territories in West Red Canyon area. Owls in these areas had

strong fidelity to breeding season roost sites: owls in 10 territories were found in the same roost areas for each of the three consecutive years, and for two years in nine other territories. In only three territories were owls found in different roost areas in consecutive years. Not every territory was occupied every year, and four occupied territories were checked during only one year. Four territories were checked for three consecutive years but owls were only located in those territories during only one year.

Twenty-eight (85 percent) of 33 different roost areas were located in canyon bottoms. Five roost areas (15 percent) were not associated with drainage bottoms and owls roosted on the upper or middle third of the slope in or adjacent to large rock cliffs. All 28 roost areas located in canyon bottoms had conifers (predominately Douglas-fir, ponderosa pine, and/or southwestern white pine) and deciduous trees within 30 meters of the roost site. Gambel oak was always present, and four roost areas also contained remnant cottonwoods. Sixteen of the canyon bottom roost areas were located in main (2nd or 3rd order) canyons and 12 were located in narrow first order drainages off of the main canyon. Of the five roost areas located in or near cliffs, four had only conifer trees within 30 meters of the roost site, while one also had Gambel oak.

Habitat Selection

The roost sites of six adult and three juvenile radio-tagged owls from the three territories in the San Mateo Mountains were used for the detailed habitat analysis. Habitat use by these birds was clearly non-random. Over two-thirds of the roost sites were located in the mixed-conifer/deciduous association (49 of 64) and the remaining sites were in mixed-conifer (15/64). No owls were found to roost in pinon-juniper or ponderosa pine forests. The distribution of roost plots among forest types was significantly different from the distribution of random plots within the owls' home ranges ($\chi^2 = 230.8$, $df=3$, $p < 0.001$, fig. 1). Percent canopy closure in roost plots ($\bar{x} = 59.2 \pm 17.2$) was significantly greater than in the full set of random plots representing all forest types ($\bar{x} = 42.6 \pm 20.1$, $p < 0.001$) but was not significantly different from mean canopy closure in the random plots in only the mixed-conifer and mixed-conifer/deciduous associations ($\bar{x} = 51.9 \pm 18.7$, $p = 0.0751$). The density of live trees was significantly greater in roost sites ($\bar{x} = 773.1 \pm 328.4$) than in random sites in all forest types ($\bar{x} = 577.9 \pm 354.1$, $p < 0.001$) but did not differ from random sites in mixed-conifer and mixed conifer/deciduous associations ($\bar{x} = 703.5 \pm 380.3$, $p > 0.05$). Mean roost tree D.B.H. was 31.1 ± 14.3 cm, mean roost tree height was 18.4 ± 6.8 meters, and mean owl roost height was 5.3 ± 2.2 meters. Most Mexican spotted owls roosted in live Douglas-fir (47 percent), Gambel oak (19 percent), or Southwestern white pine trees (13 percent).

A comparison of the basal area of tree species found in roost plots to that in random plots in all forest types (the overall comparison; table 1) found significantly higher basal area of Douglas-fir, southwestern white pine, and Gambel oak/other deciduous trees, and significantly lower pinon/juniper, in the roost plots. In contrast, when the roost plots were compared only to the subset of random plots within used habitats, the differences in Douglas-fir and white pine

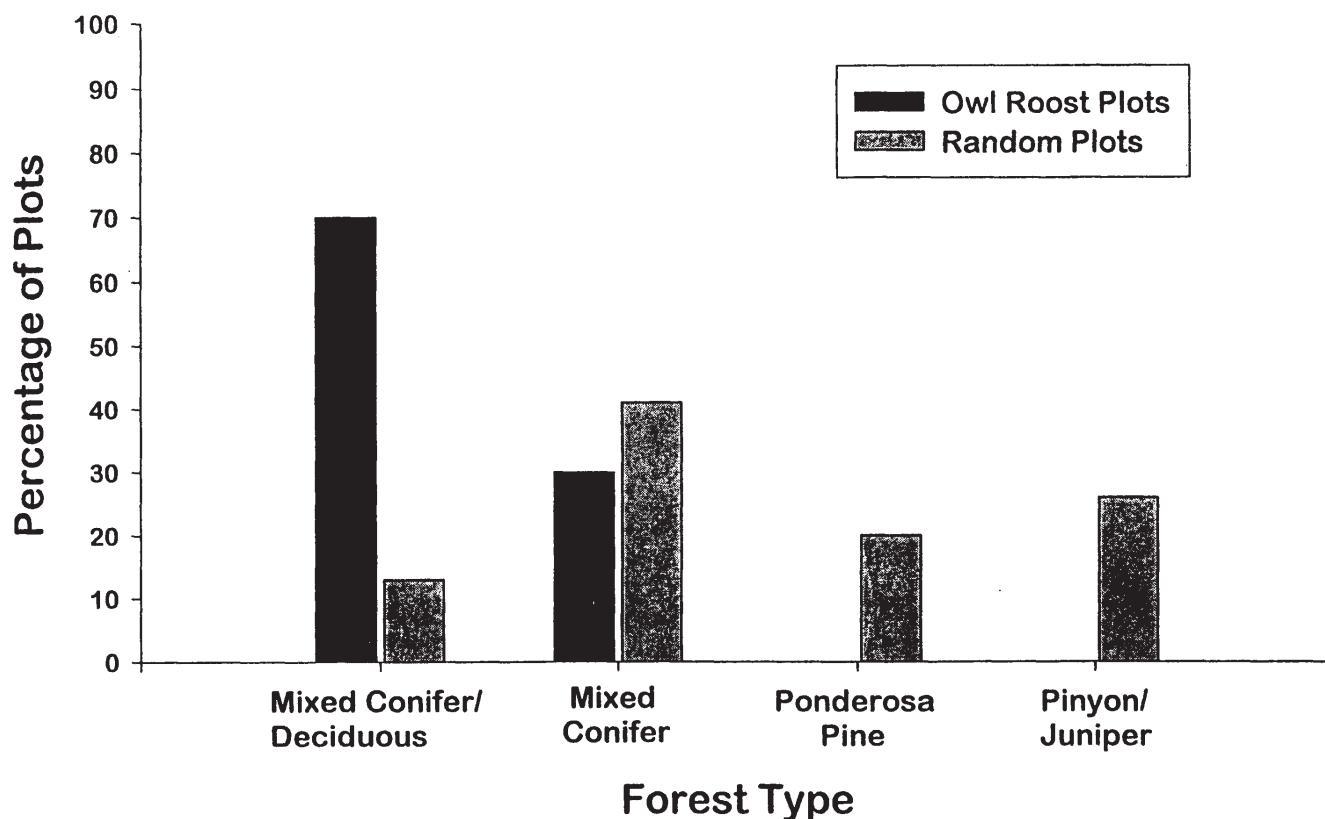


Figure 1—Distribution of Mexican spotted owl roost and randomly located sites among different forest association types in the San Mateo Mountains, Middle Rio Grande Basin, New Mexico.

Table 1—Basal areas of tree species in Mexican spotted owl roosting sites in the San Mateo Mountains, New Mexico (n = 64), compared with those in randomly selected plots within the owls' territories. Because the owls were never observed roosting in pinyon/juniper or ponderosa pine forests at our study area, we present two comparisons. First, random plots located in all forest association types in the territory (n = 69), and second, the subset of random plots that were located in forest types actually used by the owls for roosting (mixed conifer and deciduous, MC/D, and mixed conifer, MC; n = 36). Note that when the statistical influence of sample plots located in the unused forest types was removed, the difference between occupied roost sites and random plots in a higher basal area of Douglas-fir and southwestern white pine was no longer significant.

Basal Area (m ² /ha)	Roost	Means ± SD	MC/D, MC
		Random Plots All Forest Types	Forest Types
Douglas-fir	7.5 ± 6.5	3.9 ± 5.5**	6.9 ± 6.2
Southwestern White Pine	2.9 ± 6.3	0.8 ± 1.8**	1.4 ± 2.3
Pinyon/Juniper	0.2 ± 0.8	2.5 ± 4.5**	0.4 ± 1.9
Ponderosa Pine	2.9 ± 3.6	7.0 ± 7.2*	6.5 ± 5.9*
White Fir	0.6 ± 1.9	1.4 ± 4.2	2.7 ± 5.5*
Total Conifer Trees	14.2 ± 10.0	15.6 ± 8.7	18.0 ± 9.0
Gambel Oak and other Deciduous	5.5 ± 4.7	1.1 ± 2.0**	1.4 ± 2.4**
Total Live Tree	19.7 ± 9.8	16.9 ± 8.6	19.4 ± 8.9
Snags	1.8 ± 2.8	3.0 ± 4.8	4.1 ± 5.4

*, **. Statistically significant differences between occupied roost plots and random plots. Because of the large number of comparisons possible, the Bonferroni correction was used to set significance levels to * p ≤ 0.005 and ** p ≤ 0.001.

basal areas were no longer significant, and the only a greater basal area of Gambel oak and other deciduous species distinguished the occupied and random sites (table 1).

Deciduous trees also accounted for nearly three times more basal area in the roost sites than in either set of random plots, which were not different from one another: 52 percent of the total live tree basal area at roost sites versus 21 percent and 18 percent of total basal area in the random sites in all forest types and mixed-conifer or mixed-conifer/deciduous forest types, respectively.

Analysis of deciduous and coniferous tree densities in different D.B.H. classes showed significantly greater densities of small deciduous trees in the understory of roost plots, and significantly lower densities of conifers in the 15-30 cm D.B.H. class, than in either set of random plots. Surprisingly, the density of larger trees in roost plots was not significantly different from the surrounding forest matrix in either analysis. However, large deciduous and coniferous trees were only found in a few habitat plots so the power to detect a significant difference for the largest height and D.B.H. classes was low (power = 0.03-0.50). Snag densities in roost plots were only significantly different from random plots in the smallest height class (2-5 m, $p < 0.001$); these were primarily oak stems.

Discussion

Our results suggest that the habitat requirements of Mexican spotted owls may be more complicated than previously suspected. The territories of the owls in the southwest are large, often ranging from 250 to 1500 ha (USDI Fish and Wildlife Service 1995). At our study sites in both the San Mateo Mountains, as well as in the other mountain ranges, each owl territory contained 3-4 different forest types. As with most previous studies (Ganey and Balda 1994, Zwank and others 1994, Seamans and Gutiérrez 1995), we found that the birds roosted in the mixed-conifer or mixed-conifer/deciduous forest associations. No roost sites were located in pure ponderosa pine or pinyon/juniper woodlands. Like the prior studies, we also found that when we compared the characteristics of roost sites to random plots in all forest types, including those in the associations that were not used by the birds, roost sites had greater canopy closure, and greater density of Douglas-fir, southwestern white pine, Gambel oak and total live trees. But when tree species at roost sites were compared only to their availability in the used habitat types (mixed-conifer and mixed-conifer/deciduous forest types), the specific habitat characteristics important to spotted owls became even more pronounced. In this analysis, we found no significant difference in total live tree, total conifer, Douglas-fir or southwestern white pine density, or canopy closure. Roost sites and random sites in mixed conifer associations did not differ except that the occupied sites were most often in canyon bottoms or on the lower portion of slopes where there was a higher density of Gambel oak and other deciduous trees, and where deciduous trees in general made up over one-half (52 percent) of the total basal area of all live trees present. Although the detailed analysis of habitat use was conducted on only three owl territories, it is corroborated by the limited data from roost sites on 30 other territories in four mountain ranges in southwest New Mexico. In this larger sample, 84 percent of roosting areas were in canyon bottoms and contained deciduous trees.

The results of this analysis are similar to those of Rinkevich and Gutierrez (1996), who found that in Zion National Park owls occurred only in canyon bottoms with well-developed riparian vegetation, and of Johnson (1997), who found that owls in a number of different locations in Colorado always roosted in the narrow parts of canyon bottoms in areas of high canopy closure.

On the surface, our results appear to differ somewhat from those of several prior studies which have emphasized the importance of large diameter conifer trees in habitat selection (Ganey and Balda 1994, Zwank and others 1994, Seamans and Gutiérrez 1995). There are a number of reasons that may account for this. First, it is clear that the spotted owl has always occupied a number of different habitats types, including lowland bosques, and different aspects of the vegetation may be important in different parts of its range (see below). However, this study is one of the first to specifically include and quantify the basal area and densities of deciduous trees in roosting habitat, although others have noted the importance and prevalence of these species in spotted owl habitat (Ganey and others 1992, Ganey and Dick 1995, Seamans and Gutiérrez 1995, Tarango and others 1997). It also is the first to look at roost site selection only within used habitat types. Comparing roost plots to random plots throughout a study area often results in comparing roost plots in mixed-conifer forest to random plots that are located in pinyon/juniper or ponderosa pine forests. For example, approximately 30 percent of the random plots measured by Seamans and Gutiérrez (1995) at their study area in New Mexico, and 29 percent of the random plots measured in the present study, were in pinyon/juniper woodland. Only rarely have Mexican spotted owls been documented to utilize pinyon/juniper forest (Skaggs and Raitt 1988, Seamans and Gutiérrez 1995). Typical pinyon/juniper woodlands have tree cover of only 30-50 percent and the height of the tallest trees is usually only 4-8 meters (Moir and Carleton 1987). Therefore, due to the large statistical influence the unused random habitat plots may have on determining which variables are significant different among plots, it could be difficult to determine the *specific* habitat characteristics within the mixed-conifer habitat that actually affect habitat selection by the owls.

What all of these studies have in common is that they have found that Mexican spotted owls select roosting habitats are characterized by a high level structural complexity in the vegetation, just as they do in the other parts of the species range in California and the Northwest (Gutierrez and others 1995). In some parts of the southwest, this structure may be provided by old growth or mature mixed conifer forests, or by a well-developed understory of Gambel oak in ponderosa pine-oak woodlands. In many canyon habitats, however, deciduous vegetation, particularly riparian, may be the most important factor determining structural complexity. Mature montane riparian communities historically contained a wide variety of tree species, including Gambel and other oaks, cottonwoods, maples (*Acer grandidentatum*) and even conifer species such as Douglas-fir and white pine (Dick-Peddie 1993). Even today, remnant riparian habitats often contain a substantial component of Gambel oak that can provide vertical layering and vegetative structure for the birds.

Understanding the characteristics of suitable roosting habitat for spotted owls may be extremely important for a number of reasons. The birds are relatively "heat intolerant", and must find cool and shady places to roost during the summer (Barrows 1981). Intact riparian habitats, and other mature forests, are often substantially cooler than the surrounding areas. The owls simply may not be able to survive hot seasons in areas that do not have the appropriate thermal micro-environment. Spotted owls also sleep during much of the day, and during this period adult and particularly juvenile owls can be very vulnerable to diurnal and crepuscular avian predators, such as Northern goshawks (*Accipiter gentilis*) and great horned owls (*Bubo virginiana*). Typically, the owls roost in locations where multiple layers of vegetation make them difficult to detect, and they often perch on a horizontal branch next to a large tree trunk where a goshawk or great horned owl would run the risk of considerable injury if it attacked and missed its target (see also Buchanan and others 1995). Since caves and shaded sites near large cliffs can provide the same type of cool microhabitat and protection from aerial predators as do riparian areas, this may explain why the owls in our study always roosted in or near cliffs when they were not in the canyon bottoms.

As in the lowlands, canyon bottom riparian habitats in the mountains have undergone extensive alteration as a result of human activities. Many plant and animal species characteristic of this zone have become rare, and a number have been listed or been proposed for listing under the Endangered Species Act. While 88 percent of roost areas that we located, including all the canyon bottom sites, contained deciduous trees, Gambel's oak, a species found both in upland areas and canyon bottoms, was often the only deciduous species present in the immediate vicinity of roost sites. All of the canyons, however, had remnant cottonwoods and maples near the roost areas, indicating that these areas probably had more riparian characteristics before intensive grazing and other disturbances (Krueper 1993). Both our study and the results of earlier work suggest that within the mixed-conifer zone, spotted owls are selecting roost areas in canyon bottom microhabitats where deciduous trees offer the greatest vertical forest structure and canopy cover. Recognition of the canyon bottom habitat in the mixed-conifer zone as montane riparian, and monitoring of the effects of disturbance to this habitat (including grazing, road building and fire), may aid in the management of these sensitive areas. The apparent importance of deciduous vegetation in the roosting habitat selection of Mexican spotted owls suggests that the decline of montane riparian areas may have an even greater effect on biological diversity in the southwest than was originally suspected.

Acknowledgments

We thank N. Cervantes, T. Epps, L. Graham, J. Hobson, K. Marty, C. Thompson and M. Watson for their dedicated help with the field work. J. Ganey, W. Block, J. Berger, M. Gomper, and K. Obermeyer provided helpful discussion of the ideas. We thank S. Spangle of the U.S. Fish and Wildlife Service, Albuquerque, N.M. and W. Block of the Rocky Mountain Forest and Range Experiment Station, U.S. Forest Service, for facilitating this study. Funding was provided

by U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station Cooperative Agreement 28-C3-741 and National Science Foundation Grant DEB 9302247 to PBS, and a Cooper Ornithological Society Mewaldt-King Student Research Award to AH.

References

- Arsenault, D.A.; Hodgson, A.; Stacey, P.B. 1997. Dispersal movements of juvenile Mexican spotted owls (*Strix occidentalis lucida*) in New Mexico. In J.R. Duncan, D.H. Johnson, and T.H. Nichols, eds. Biology and Conservation of Owls of the Northern Hemisphere. USDA Forest Service Gen. Tech. Rept. NC-190, St. Paul, MN: 47-57.
- Bailey, F.M. 1928. Birds of New Mexico. New Mexico Department of Game and Fish. Santa Fe, NM.
- Buchanan J.B.; Irwin L.I.; McCutchen E.L. 1995. Within-stand nest-site selection by spotted owls in the eastern Washington Cascades. J. Wildlife Manage. 59:301-310.
- Dick-Peddie, W.A. 1993. New Mexico vegetation, past present and future. Albuquerque, NM: University of New Mexico Press. 246p.
- Forsman, E.D. 1983. Methods and materials for locating and studying spotted owls. USDA Forest Service Gen. Tech. Rept. PNW-162, Pacific Northwest Research Station, Portland, OR.
- Forsman, E.D.; Meslow, E.C. and Wright, H.M. 1984. Distribution and biology of the spotted owl in Oregon. Wild. Monogr. 87:1-64.
- Ganey, J.L.; Balda, R.P. 1994. Habitat selection by Mexican spotted owls in northern Arizona. Auk 111:162-169.
- Ganey, J.L.; Dick, J.L. Jr. 1995. Habitat relationships of the Mexican spotted owl: Current knowledge. Chapter 4. In USDI Fish and Wildlife Service. Recovery plan for the Mexican spotted owl (*Strix occidentalis lucida*), Vol. 2. Albuquerque, NM.
- Ganey, J.L.; Duncan, R.B.; Block, W.M. 1992. Use of oak and associated woodlands by Mexican spotted owls in Arizona. In Folliott, P.F., G.J. Gottfried, D.A. Bennett, V.M. Hernandez C., A. Ortega-Rubio, and R.H. Hamre [tech. coords.], Ecology and management of oak and associated woodlands: perspectives in the southwestern United States and northern Mexico. USDA Forest Service Gen. Tech. Rept. RM-218, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Hodgson, A.; Stacey, P.B. 1996. Dispersal and habitat use of Mexican spotted owls in New Mexico. Final Report, USDA Forest Service, Cooperative Agreement 28-C3-741. Rocky Mountain Experiment Station, Fort Collins, CO.
- Johnson, C.L. 1997. Distribution, habitat and ecology of the Mexican spotted owl in Colorado. Master's Thesis, University of Northern Colorado, Greeley, CO.
- Krueper, D.J. 1993. Effects of land use practices on western riparian ecosystems. In D.M. Finch and P.W. Stangel [eds.], Status and management of neotropical migratory birds. USDA Forest Service Gen. Tech. Rept. RM-229, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Kuntz, W.A.; Stacey, P.B. 1997. Preliminary investigation of vocal variation in the Mexican spotted owl (*Strix occidentalis lucida*): Would vocal analysis of the four-note location call be a useful tool for field identification? In J.R. Duncan, D.H. Johnson, and T.H. Nichols, eds. Biology and Conservation of Owls of the Northern Hemisphere. USDA Forest Service Gen. Tech. Rept. NC-190, North Central Research Station, St. Paul, MN: 562-568.
- Ligon, J.S. Habits of the spotted owl (*Syrnium occidentale*). Auk 43:421-429.
- Manly, B.F.J. 1994. Multivariate statistical methods: a primer, 2nd ed. Chapman and Hall, London, UK.
- Moir, W.H.; Carleton, J.O. 1987. Classification of pinyon-juniper (P-J) sites on National Forests in the Southwest, p. 216-226. In Proceedings Pinyon-Juniper Conference. USDA Forest Service Gen. Tech. Rept. INT-215, Intermountain Research Station, Ogden, UT.
- Phillips, A.; Marshall, J.; Monsen, G. 1964. Birds of Arizona. University of Arizona Press. Tucson, AZ.
- Rinkevich S.E.; Gutierrez R.J. 1996. Mexican spotted owl habitat characteristics in Zion National Park. J. Raptor Research. 30:74-78.

- Sas Institute. 1988. SAS/STAT User's Guide, Release 6.03. SAS Institute, Cary, North Carolina, USA.
- Seamans, M.E.; Gutiérrez, R.J. 1995. Breeding habitat of the Mexican spotted owl in the Tularosa Mountains, New Mexico. *Condor* 97:944-952.
- Skaggs, R.W.; Raitt, R.J. 1988. A spotted owl inventory of the Lincoln National Forest, Sacramento Division, 1988. Unpublished Report to the New Mexico Department of Game and Fish, Santa Fe. 12 pp.
- Tarango L.A.; Valdez R.; Zwank P.J.; Cardenas, M. 1997. Mexican spotted owl habitat characteristics in southwestern Chihuahua, Mexico. *Southwestern Nat.* 42:132-136.
- USDI Fish And Wildlife Service. 1993. Endangered and threatened wildlife and plants; final rule to list the Mexican spotted owl as a threatened species. *Federal Register* 58:14248-14271.
- USDI Fish And Wildlife Service. 1995. Recovery plan for the Mexican spotted owl (*Strix occidentalis lucida*), Volume 1. Albuquerque, NM. 172 pp.
- Wiley, D.W. 1993. Home-range characteristics and juvenile dispersal ecology of Mexican spotted owls in southern Utah. Unpublished Report to the Utah Division of Wildlife Resources, Salt Lake City.
- Zwank, P.J.; Kroel, K.W.; Levin, D.M.; Southward, G.M.; Romme, R.C. 1994. Habitat characteristics of Mexican spotted owls in southern New Mexico. *J. Field Ornithol.* 65: 324-334.

Riparian Dependence, Biogeographic Status, and Likelihood of Endangerment in Landbirds of the Southwest

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R. Roy Johnson

Abstract—Riparian habitats and wetlands represent less than 2 percent of the land area of the Southwest, but they support the highest density and abundance of plants and animals in that region (Dahms and Geils 1997). Since the latter part of the 19th century, riparian and wetland ecosystems have been severely impacted by human activities such as woodcutting, mining, livestock grazing, and water diversion and pumping (Phillips and Monson 1964, Johnson and Carothers 1982, Tellman and others 1997). In this paper, we examine the likelihood of species endangerment in obligate and preferential riparian-nesting landbirds of the Southwest. Population trends are also reviewed with respect to biogeography, as we distinguish between birds that reach the end of their distribution in the Southwest and those that do not. We report local extirpations and/or population declines for a higher proportion of those species occurring at the northern periphery of their geographic range. We also show an increased likelihood of endangerment for obligate vs. preferential riparian birds. Ultimately, the large number of Southwestern species depending on riparian habitats and/or represented by peripheral populations only underscores the sensitivity of the regional avifauna to riparian habitat degradation.

With a disproportionate percentage of the nation's vertebrate species, the southwestern United States is known as a region of high biodiversity (Hubbard 1977). A relatively low latitude, a varied topography, a unique biogeographic and geologic history (MacMahon 1985, Flather and others 1994), and the local occurrence of most of the vegetative life zones/biotic communities of the western U.S. (Carleton and others 1991, Brown 1994) all contribute towards high species richness. An important feature of biodiversity in the Southwest, however, is that much of the wildlife is concentrated in riparian habitats and wetlands, which constitute less than 2 percent of the land area (Johnson and Haight 1985, Szaro and Jakle 1985, Dahms and Geils 1997). Birds in particular show a close association with riparian habitats and wetlands, as 78 (47 percent) of the 166 avian species nesting in the Southwest lowlands are completely dependent on these

habitats during the breeding season (Johnson and others 1977).

Another important feature of the regional wildlife relates to biogeography: many of the vertebrate species (for example, birds, bats) represented in the Southwest reach the end of their distribution in this region. Because population density tends to decline (Hengeveld and Haeck 1982, Rapoport 1982, Brown 1984, Emlen and others 1986, Telleria and Santos 1993, Maurer and Villard 1994, Brown and others 1995) and distribution may be patchier (Brown 1984) towards the edge of the geographic range, peripheral populations tend to be small and isolated. Hence, they may be associated with a higher risk of occasional decline or even local extirpation due to stochastic variation in local conditions (see Petterson 1985, Simberloff 1988, Clark and others 1990). Ultimately, the high concentration of wildlife in only a small portion of the land area, combined with the large number of species represented by peripheral populations - which, too, may concentrate near bodies of water - suggests that biological diversity in the Southwest may be particularly vulnerable to the loss of riparian habitat and wetlands.

In this study, we examine the influence of biogeography and extent of riparian dependence on the prevalence and/or likelihood of endangerment in landbirds nesting at low and mid elevations in Arizona and New Mexico. As it turns out, riparian habitats have been severely altered by human activities since the end of the 19th century. Due to ground-water pumping, livestock grazing, water management activities, urban expansion, woodcutting, invasion by exotic species, and mining (Phillips and Monson 1964, Rea 1983, Johnson and Simpson 1988, Tellman and others 1997), an estimated 90 to 95 percent of the original riparian habitat has been lost or degraded (Johnson and Carothers 1982, Fleishner 1994). Altogether, the history of riparian habitats in the Southwest has been called one of destruction and desertification (Phillips and Monson 1964, Johnson and Simpson 1988).

Methods

We first compiled a list of all 74 obligate and preferential riparian/wetland landbird species breeding at low or mid elevations (i.e., desertscrub and desert grasslands) in Arizona and New Mexico (table 1). Obligate riparian species were those nesting (almost) exclusively in riparian habitats, while preferential riparian birds were those breeding most frequently and in highest numbers along rivers and streams. The differentiation between obligates and preferentials, as

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Table 1—List of obligate and preferential riparian and wetland landbird species nesting at low and mid-elevations in the Southwest (Arizona and New Mexico).

Species (Federal and State status) ^a	Geographic status ^b	Population decline/extirpation ^c
Obligate riparian and wetland		
Mississippi Kite (AZ)		
Bald Eagle (FT)	SE	
Cooper's Hawk		EEE
Common Black-Hawk (AZ, NM)	NE	E
Gray Hawk (AZ)	NE	E
Zone-tailed Hawk	NE	E
Yellow-billed Cuckoo (AZ)		DDDD
Broad-billed Hummingbird (NM)	NE	
Violet-crowned Hummingbird (AZ)	NE	
Belted Kingfisher (AZ)	SE	extirpated in the lowlands
Northern Flicker (Red-shafted race)		
Northern Beardless-Tyrannulet (NM)	NE	
Western Wood Pewee		
Willow Flycatcher (FE)	SE	EEEE
Black Phoebe		
Vermilion Flycatcher	NE	EEED
Tropical Kingbird (AZ)	NE	
Cassin's Kingbird		
Thicket-billed Kingbird (AZ, NM)	NE	
Western Kingbird		
Rose-throated Becard (AZ)	NE	E
Bank Swallow	SE	
Cliff Swallow		
White-breasted Nuthatch		
Bewick's Wren		
Marsh Wren	SE	
Yellow Warbler		
Common Yellowthroat		
Yellow-breasted Chat		EED
Red-winged Blackbird		
Yellow-headed Blackbird	SE	
Summer Tanager	NE	EEED
Blue Grosbeak		
Lazuli Bunting	SE	
Indigo Bunting	SE	
Painted Bunting	NE	
Song Sparrow		
Abert's Towhee (NM)		
Bronzed Cowbird	NE	
Northern Oriole		
Lesser Goldfinch		
Preferential riparian		
Harris' Hawk	NE	EEEE
American Kestrel		
Peregrine Falcon (FE)		
Gambel's Quail		
White-winged Dove	NE	
Mourning Dove		
Common Ground Dove (NM)	NE	
Greater Roadrunner		
Common Barn Owl		
Western Screech-Owl		
Ferruginous Pygmy-Owl (FE)	NE	EEEE
Elf Owl	NE	DDDD
Black-chinned Hummingbird		
Anna's Hummingbird	NE	
Gila Woodpecker (NM)	NE	D
Ladder-backed woodpecker		
Ash-throated Flycatcher		
Brown-crested Flycatcher	NE	EEE

(con.)

Table 1 (Con.)

Species (Federal and State status) ^a	Geographic status ^b	Population decline/extirpation ^c
Preferential riparian (con.)		
Northern Rough-winged Swallow		
Verdin	NE	
Black-tailed Gnatcatcher	NE	
Northern Mockingbird		
Curve-billed Thrasher		
Crissal Thrasher	NE	
Phainopepla	NE	
European Starling		
Bell's Vireo	NE	DDED-E
Lucy's Warbler		
Northern Cardinal	NE	
Pyrrhuloxia	NE	
Brown-headed Cowbird		
Hooded Oriole	NE	EEE
House Finch		

Data compiled from Monson and Phillips (1981), Hunter and others (1987), Johnson and others (1987), Arizona Game and Fish Department (1988, 1996), U.S. Fish and Wildlife Service (1996), New Mexico Department of Game and Fish (1997).

^aFE: federally listed as endangered in Arizona and/or New Mexico, FT: federally listed as threatened in Arizona and/or New Mexico, AZ: listed by the Arizona Game and Fish Department as endangered, threatened, or candidate (i.e., species or subspecies for which threats are known or suspected and substantial population declines probably occurred but have not been documented), NM: listed by the New Mexico Department of Game and Fish as endangered, threatened, or sensitive.

^bNE: occurs at the northern edge of its geographic range in the Southwest, SE: occurs at the southern edge of its geographic range in the Southwest.

^cE: extirpated from the upper basin of one major river (Salt, Verde, Gila, Colorado, Santa Cruz, San Pedro rivers, Rio Grande) and its tributaries, EE: extirpated from the upper basin of two major rivers,... D: population decline documented within the upper basin of one major river, DD: population decline documented within the upper basin of two major rivers,...

presented here, was specific both to low and mid-elevations and to Arizona and New Mexico only. The Yellow-billed Cuckoo (*Coccyzus americanus*), for example, is widespread in a variety of mesic habitats in the eastern states, but it is restricted to riparian woodlands in the Southwest. The Cassin's Kingbird (*Tyrannus vociferans*) is an obligate riparian bird at lower elevations, but in pinyon-juniper woodlands it often nests away from water.

We also determined the biogeographic status of each species in relation to the northern and southern ends of its distribution. Birds were divided into three categories: a) species that reach the northern end of their range in the Southwest, b) species that reach the southern end of their range in the Southwest, and c) all other species. For each species, likelihood of endangerment was then examined using two indicators: (1) population decline or local extirpation documented in the lower basin of one or several major watersheds (Colorado, Gila, Salt, Verde, San Pedro, Santa Cruz, Rio Grande) and (2) federal or state listing as endangered, threatened, candidate, or sensitive species. The second indicator did not reflect endangerment per se, as listing can also be based on scarcity in the absence of population decline. However, scarcity may determine the potential risk for future population decline and/or extirpation (see introduction). Differences in the number of species exhibiting population decline or local extirpation were tested across the categories defined above. Differences in the number of species listed on the Federal Register and/or by states were tested between obligate and preferential birds. All statistical tests consisted of Chi-square analyses of contingency tables.

Results and Discussion

Of all 74 species listed in our table (table 1), 41 (55 percent) were found to be riparian obligates, 33 (45 percent) preferentials. A total of 37 (50 percent) birds reached the northern or the southern end of their geographic range in the Southwest. Population decline and/or extirpation was documented for 18 (24 percent) species, while federal or state listing was reported for 18 (24 percent) birds -but not necessarily the same species exhibiting decline or extirpation. Results indicated a significantly higher ($P < 0.005$) proportion of species exhibiting population decline and/or local extirpation among those occurring at the northern end of their geographic range than among those not occurring at the end of their distribution (fig. 1). The difference in the proportion of species showing population decline/local extirpation between biogeographic categories b -represented by only 8 species- and c was three-fold, but failed to achieve significance ($P > 0.05$). No significant difference ($P > 0.05$) was detected in the proportion of obligate versus preferential riparian species showing population decline and/or local extirpation. However, the proportion of species listed versus not listed was significantly higher ($P < 0.05$) in obligate birds than in preferential birds. Combining indicators 1 and 2 (see methods), the proportion of obligate species exhibiting endangerment and/or scarcity was marginally significantly higher ($P < 0.1$) than that of preferential species (fig. 2).

Overall, our study underlines the fragile nature of the southwestern avifauna: if biogeographic status and extent of riparian dependence influence the likelihood of

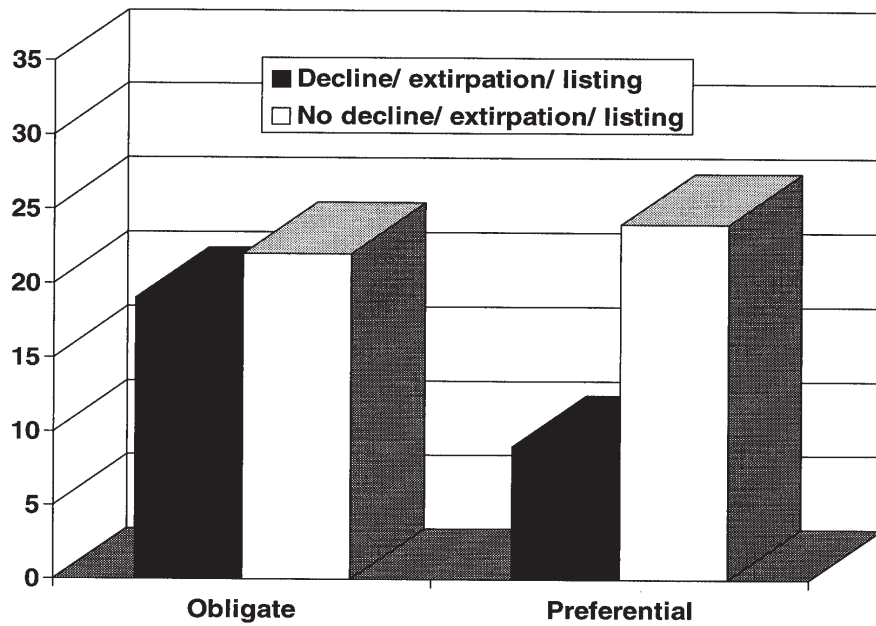


Figure 1—The influence of biogeography. The Y axis represents the number of bird species exhibiting versus not exhibiting population decline and/or local extirpations across three biogeographic categories: (1) birds that reach the northern end of their range in the Southwest (Periph. [N]), (2) birds that reach the southern end of their range in the Southwest (Periph. [S]), and (3) all other species.

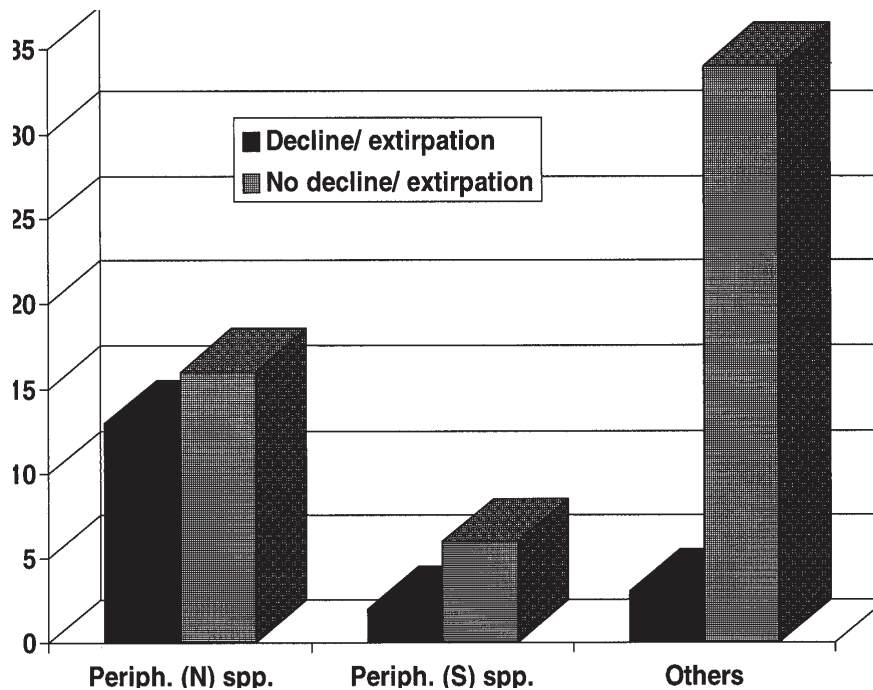


Figure 2—The relationship between extent of riparian dependence and population scarcity and/or endangerment. The Y axis represents the number of riparian birds state/federally listed and/or exhibiting population decline or local extirpation across two categories: (1) obligate riparian birds and (2) preferential riparian birds.

endangerment, then a high number of species—those exhibiting a high degree of dependence on riparian habitats and/or those represented by peripheral populations—may be at risk for becoming extirpated in the Southwest if habitat degradation continues. The study may also be useful for predicting which birds may be vulnerable to further degradation of riparian habitats. In our view, conservation planning for peripheral populations may be more important than generally advocated by biologists: reduced gene flow between isolated peripheral populations and core populations may well signify a greater potential for speciation at the edge of the geographic range (Brown 1984). Continued habitat loss may then mean not only reduced biodiversity but also decreased potential for speciation—arguably one key determinant of future biodiversity.

References

- Arizona Game and Fish Department. 1988. Threatened native wildlife in Arizona. Phoenix, AZ: Arizona Game and Fish Department. 32 p.
- Arizona Game and Fish Department. 1996. Wildlife of special concern in Arizona (Public Review Draft). Phoenix, AZ: Nongame and Endangered Wildlife Program, Arizona Game and Fish Department. 40 p.
- Brown, D. E. (ed.). 1994. Biotic communities of the southwestern United States and northwest Mexico. Salt Lake City, UT: University of Utah Press. 342 p.
- Brown, J. H. 1984. On the relationship between abundance and distribution of species. *American Naturalist* 124: 255-279.
- Brown, J. H., D. W. Mehlman, and G. C. Stevens. 1995. Spatial variation in abundance. *Ecology* 76(7):2028-2043.
- Carleton, J. O., W. A. Robbie, G. T. Robertson, C. L. Spann, H. G. Brown, III, J. Glass, D. W. Shaw, T. Robison, W. H. Moir, D. Potter, R. A. Fletcher, R. Galeano-Popp, and G. J. Miller. 1991. General ecosystem survey. Albuquerque, NM: U.S. Department of Agriculture, Forest Service. 188 p. plus maps.
- Clark, T. W., R. M. Warnecke, and G. G. George. 1990. Management and conservation of small populations. In: T. W. Clark and J. H. Seebeck, eds. *Management and conservation of small populations*. Brookfield, IL: Chicago Zoological Society.
- Dahms, C. W., and B. W. Geils, eds. 1997. An assessment of forest ecosystem health in the Southwest. Gen. Tech. Rep. RM-GTR-295. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Emlen, J. T., M. J. DeJong, M. J. Jaeger, T. C. Moermond, K. A. Rusterholz, and R. P. White. 1986. Density trends and range boundary constraints of forest birds along a latitudinal gradient. *Auk* 103:791-803.
- Flather, C. H., L. A. Joyce, and C. A. Bloomgarden. 1994. Species endangerment patterns in the United States. Gen. Tech. Rep. RM-241. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Fleishner, T. L. 1994. Ecological costs of livestock grazing in western North America. *Conservation Biology* 8:629-638.
- Hengeveld, R., and J. Haack. 1982. The distribution of abundance. I. Measurements. *Journal of Biogeography* 9:303-316.
- Hubbard, J. P. 1977. Importance of riparian ecosystems: biotic considerations. Pp 14-18. In: R. R. Johnson and D. A. Jones, tech. eds. *Importance, preservation, and management of riparian habitat: a symposium*. Gen. Tech. Rep. RM-43. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment.
- Hunter, W. C., R. D. Ohmart, and B. W. Anderson. 1987. Status of breeding riparian-obligate birds in southwestern riverine systems. *Western Birds* 18(1):10-18.
- Johnson, R. R., and S. W. Carothers. 1982. Riparian habitat and recreation: interrelationships and impacts in the Southwest and Rocky Mountain Region. *Eisenhower Consortium Bulletin* 12:1-31. Fort Collins, CO: U.S. Department of Agriculture, Rocky Mountain Forest and Range Experiment Station.
- Johnson, R. R., and L. T. Haight. 1985. Avian use of xeroriparian ecosystems in the North American warm deserts. Pp 156-160. In: R. R. Johnson, C. D. Ziebel, D. R. Patton, P. F. Folliot, and R. H. Hamre, eds. *Riparian ecosystems and their management: Reconciling conflicting uses*. Gen. Tech. Rep. RM-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Johnson, R. R., L. T. Haight, and J. M. Simpson. 1977. Endangered species vs. endangered habitats: a concept. Pp. 68-79. In: R. R. Johnson and D. A. Jones, tech. coords. *Importance, preservation and management of riparian habitat: A symposium*. Gen. Tech. Rep. RM-43. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.
- Johnson, R. R., L. T. Haight, and J. M. Simpson. 1987. Endangered habitats versus endangered species: a management challenge. *Western Birds* 18(7):89-96.
- Johnson, R. R., and J. M. Simpson. 1988. Desertification of wet riparian ecosystems in arid regions of the North American Southwest. Pp. 1383-1393. In: E. E. Whitehead, C. F. Hutchinson, B. N. Timmermann, and R. G. Varady, eds. *Arid lands: today and tomorrow*. Boulder, CO: Westview Press.
- MacMahon, J. A. 1985. *Deserts*. New York, NY: Alfred A. Knopf, Inc. 640 p.
- Maurer, B. A., and M.-A. Villard. 1994. Population density: geographic variation in abundance of North American birds. *National Geographic Research and Exploration* 10:306-317.
- Monson, G., and A. R. Phillips. 1981. Annotated checklist of the birds of Arizona, 2nd edition. Tucson, AZ: University of Arizona Press. 240 pp.
- New Mexico Department of Game and Fish. 1997. *New Mexican wildlife of special concern*. Santa Fe, NM: New Mexico Department of Game and Fish, Conservation Services Division.
- Pettersson, B. 1985. Extinction of an isolated population of the middle spotted woodpecker *Dendrocopos medius* (L.) in Sweden and its relation to general theories on extinction. *Biological Conservation* 32:335-353.
- Phillips, A. R., and G. Monson. 1964. Historic changes and conservation of Arizona habitats. Pp. ii-xvii. In: A. R. Phillips, J. Marshall, and G. Monson. *The birds of Arizona*. Tucson, AZ: University of Arizona Press.
- Rapoport, E. H. 1982. *Aerography: Geographical strategies of species*. Oxford: Pergamon.
- Rea, A. M. 1983. *Once a river*. Tucson, AZ: University of Arizona Press.
- Szaro, R. C., and M. D. Jakle. 1985. Avian use of a desert riparian island and its adjacent scrub habitat. *Condor* 87:511-519.
- Simberloff, D. 1988. The contributions of population and community biology to conservation science. *Annual Review of Ecology and Systematics* 19:473-511.
- Telleria, J. L., and T. Santos. 1993. Distributional patterns of insectivorous passerines in the Iberian Forests: does abundance decrease near the border? *Journal of Biogeography* 20:235-240.
- Tellman, B., R. Yarde, and M. G. Wallace. 1997. *Arizona's changing rivers: How people have affected the rivers*. Tucson, AZ: Water Resources Research Center, College of Agriculture, University of Arizona.
- U.S. Fish and Wildlife Service. 1996. *Endangered and threatened wildlife and plants*. 50 CFR 17.11 and 17.12. Washington, D.C.: U.S. Fish and Wildlife Service.

Arthropods of Native and Exotic Vegetation and Their Association with Willow Flycatchers and Wilson's Warblers

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Abstract—We compared abundance of migrating Willow Flycatchers and Wilson's Warblers to the abundance of arthropods in exotic and native vegetation at Bosque del Apache National Wildlife Refuge. We trapped arthropods using glue-boards in 1996 and 1997 in the same cottonwood, saltcedar, and willow habitats where we mist-netted birds during spring and fall migration. There were fewer arthropods, particularly flies, in saltcedar. We have mixed evidence that Willow Flycatchers and Wilson's Warblers respond to variation in insect numbers. Wilson's Warblers appear to be more abundant in willow than in other vegetation types in response to the abundance of small flies.

Desert riparian forests in the Southwestern United States attract a higher concentration of migrating passerines and are a valuable resource for breeding birds (Ohmart 1994, Finch and others 1995). Little is known about what types of habitats are most important during landbird migration or how habitat alteration may affect migrating birds (Moore and others 1995). The Rio Grande is the second largest riparian system in the Southwest and supports the largest cottonwood forest in North America (Whitney 1994). Exotic tree species are a major component of riparian forests. We are evaluating the relative importance of exotic and native vegetation types to migrating landbirds and the relationship of arthropod prey to avian use of vegetation at Bosque del Apache National Wildlife Refuge.

Methods

We captured passerine birds using mist-nets and sampled their potential arthropod prey using glue-boards in three adjacent vegetation types at Bosque del Apache National Wildlife Refuge (33°48'N, 106°52'W), New Mexico.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Vegetation Types—We classified the vegetation as: Fremont cottonwood (*Populus fremontii*) forest, coyote willow (*Salix exigua*) stringers along water conveyance structures, and saltcedar (*Tamarix ramosissima*) forest. The cottonwood forest had a mature cottonwood overstory of 30 percent coverage with a fairly closed middle story of exotic saltcedar and Russian olive (*Eleagnus angustifolia*) and young cottonwood and Gooding willow (*S. gooddingii*). The tree-shrub layer, approximately 5 meters in height, was sparse and included seepwillow (*Baccharis* spp.) and pale wolfberry (*Lycium pallidum*). The willow stands along water conveyance channels were fairly homogeneous, dense, periodically mowed, and reached only 5 meters in height. Two separate conveyance structures were studied, but were combined as a single willow vegetation type. The saltcedar forest was dominated by a tree-shrub layer (5 meters in height) of saltcedar. There were as many dead stems as live ones and the forest structure was a mixture of densely clumped shrubs and open ground (M. Means, pers. obs.).

Bird abundance—We estimated bird relative abundance as captures per net-hour using nylon mist nets (12 meters x 2.6 meters) opportunistically placed in each habitat. We set up between 28 to 31 nets distributed as follows: 6 to 7 in cottonwood, 16 to 18 in willow, and 5 to 7 in saltcedar. Nets were opened 15 minutes before dawn and left open for an average of 6 hours each day for 5 days a week. Field data were collected in 1996 and 1997 during spring migration (late April to early June) and fall migration (early August to early November). We selected two Neotropical migrant passerines for our in-depth analysis of bird-arthropod associations: a commonly captured, primarily foliage gleaning bird (Wilson's Warbler, *Wilsonia pusilla*) and a rarer, primarily aerial forager (Willow Flycatcher, *Empidonax traillii*).

Arthropod prey abundance—Glue-board traps were used to sample arthropods for one 24 hour period each week. These glue-boards were placed at a subset of mist-nets within each vegetation type where they were randomly attached to the vegetation 1.5 meters from the ground within 10 meters of a mist-net. Glue-boards were yellow, approximately 13 cm x 18 cm, and coated with Tanglefoot™. Arthropods trapped on glue-boards were counted and grouped into size categories, small (≤6 mm), medium (>6 to 12 mm), and large (>12 mm), and identified to Order and Family.

Our arthropod sampling scheme (see Hutto 1980, Cooper and Whitmore 1990 for discussion on the efficiency of this

method) was set up primarily for ease of operation and to estimate general abundance of arthropods in relation to the relative abundance of birds captured in the immediate vicinity. With this single sampling method, we do not claim to be sampling the same prey species that aerial gleaning and foliage gleaning insectivores are capturing. We are assuming that prey numbers correlate with those of arthropod availability. For a more adequate picture of availability (see Hutto 1985), we incorporated differences in vegetation density (foraging-substrate availability) among vegetation types into our estimates of arthropod availability. Assuming independence of arthropods captured and vegetation density between vegetation types, we calculated a relative index of arthropod numbers adjusted by a measure of shrub density (<5 meters in height). We calculated the average number of shrub stems for a habitat from 0.04 ha areas around each net and divided the number by 1000. We then multiplied that vegetation density by the number of arthropods per trap.

Analysis—Statistical analyses were performed with SPSS/PC+ (SPSS 1994) or SAS/PC (SAS Institute 1990). Normality and homogeneity were examined prior to applying parametric and nonparametric tests. Univariate analysis of variance was performed using PROC GLM (SAS Institute 1990) to test for differences in arthropod abundances among vegetation types for each year and season. Numerically important orders of arthropods were identified, and separate ANOVA tests were performed for each group. Duncan's multiple range test was used to determine which mean values from each vegetation type were different, and Bonferroni adjustments in significance levels were made when needed (Rice 1989). The arthropod count data were log-transformed for the ANOVA tests. Associations between arthropod abundance and bird abundance were tested with the nonparametric Spearman's rank correlation test (SPSS 1994). A Wilcoxon 2-tailed test was used to examine differences in two size classes of flies. An alpha level of 0.05 was used to signify significance.

Results

Fifteen orders of arthropods were represented on glueboards set out in cottonwood midstory, stands of willow, and stands of saltcedar forest. Coleopteran, Dipteran, Hemipteran, Homopteran, Hymenopteran, and adult Lepidopteran were represented in samples in both seasons and years in all three habitats (table 1).

There were significant year and season differences among the relative abundances of insects (2-way ANOVA: $F=1.24$, $df=$ $P=0.002$) and the seasonal difference depended on the year (year*season, $F=9.24$, $df=$ $P=0.003$). Subsequent comparisons between vegetation types were therefore examined separately by year and season. The relative abundance of arthropods was significantly less in saltcedar than in willow or cottonwood midstory in most years and seasons. Arthropod numbers per trap were highly variable in saltcedar during fall, 1997, and did not differ from those in willow or cottonwood (fig. 1, table 2). Patterns in the data differed when we corrected arthropod abundance for shrub density (arthropod-shrub index, table 2). There were significantly fewer arthropods (arthropod-shrub index) in the cottonwood understory than in willow for most comparisons.

Flies were less abundant in the homogenous stands of saltcedar than in the other vegetation for both years and seasons. There were more orders (5 out of 6) in the fall of 1997, in which differences among vegetation were evident (table 2).

Beetles (Coleoptera) and plant bugs (Homoptera) are primarily foliage inhabiting insects and made up the largest proportion (83 percent in 1996 and 77 percent in 1997) of that group. Flies (Diptera) and wasps, etc. (Hymenoptera) made up the greatest proportion of aerial insects (99 percent, both 1996 and 1997). We examined the association of both aerial insects (flies and wasps) and foliage insects (beetles and plant bugs) with Wilson's Warblers (WIWA) and Willow Flycatchers (WIFL) over time for 1996 and 1997. Over time there was a positive association between the relative

Table 1—Orders of arthropods represented by season (S=spring, F=fall) in the three habitats sampled, 1996 and 1997.

Order	Cottonwood		Willow		Saltcedar	
	1996	1997	1996	1997	1996	1997
ACARINA (mites)	S F	F	F	F		
ARANEIDA (spiders)	S F	S F	S F	S F	S F	F
COLEOPTERA (beetles)	S F	S F	S F	S F	S F	S F
DERMAPTERA (earwigs)	F					
DIPTERA (flies)	S F	S F	S F	S F	S F	S F
EPHEMEROPTERA (mayflies, etc.)				F		
HEMIPTERA (true bugs)	S F	S F	S F	S F	S F	S F
HOMOPTERA (plant bugs)	S F	S F	S F	S F	S F	S F
HYMENOPTERA (wasp, etc.)	S F	S F	S F	S F	S F	S F
LEPIDOPTERA (adult butterflies, etc.)	S F	S F	S F	S F	S F	S F
ODONATA (dragonflies, etc.):			F	S		
ORTHOPTERA (grasshoppers, etc.):			F	S F		S
THYSANURA (bristletails):	S F					
THYSANOPTERA (thrips):	S F	S F	S F	S F	S F	S F
TRICHOPTERA (caddisflies):		S F	F	S F		

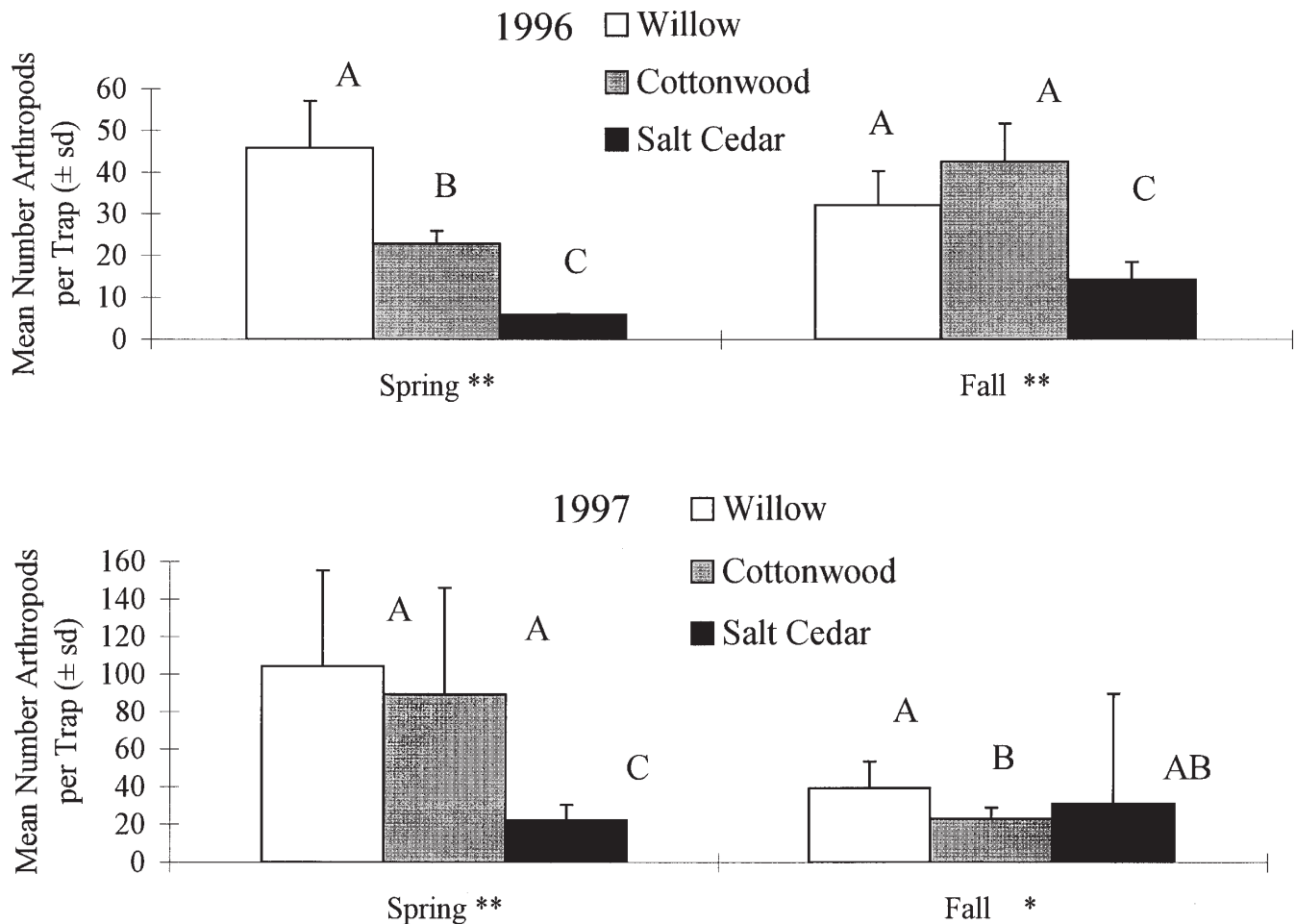


Figure 1 — The mean relative abundance of all arthropods found in three vegetation types during spring and fall, 1996 and 1997.

abundance of Willow Flycatchers and the relative abundance of aerial insects in 1996 (Spearman's rho 0.89, $P=0.001$, $N=9$) but not in 1997 (Spearman's rho 0.12, $P=0.60$, $N=15$). In spring of 1997, WIFL numbers tended to correspond with that of aerial insects, although this pattern was not significant (Spearman's rho 0.7, $P=0.17$, fig. 2).

Wilson's Warblers were not associated with aerial insects over all weeks sampled in 1996 (Spearman's rho 0.42, $P=0.26$, $N=9$) and tended to show only a trend in 1997 (Spearman's rho 0.50, $P=0.06$, $N=15$). However, Wilson's Warbler numbers appeared to respond to temporal changes in aerial and foliage insect numbers over the spring season of both years (fig. 3). There was a positive association between their relative abundance with that of aerial (Spearman's rho=0.90, $P=0.04$, $N=5$) and foliage (Spearman's rho=0.99, $P=0.0001$, $N=5$) insects in the spring.

Wilson's Warbler numbers showed a corresponding association with aerial insects only in the willows in 1997 (Spearman's rho=0.65, $P=0.009$, $N=15$). There were significantly more small flies (<6mm) than mid to large flies (≥ 6 mm) in the willows in 1997 (Wilcoxon 2-tailed, $P=0.0001$). The greatest proportion of small flies consisted of Hump-backed flies (Phoridae) and Long-legged flies (Dolichopodidae); flies that tend to hover about the foliage. Together

they comprised 31 percent of flies in the spring and increased to 67 percent in the fall. Gnats, chironomids, mosquitoes and other swarming nematocerans comprised 61 percent of the flies in spring and dropped to 19 percent in the fall.

Discussion

Migration is energetically stressful and migrants must stopover between breeding and wintering habitats to forage, rest, and replenish fat deposits (Moore and others 1995). Decisions involved in habitat selection by landbird migrants may depend on the spatial scale examined. The decision to stop along a particular route on the way between wintering and breeding grounds may be driven by such extrinsic factors as genetics or associated with the benefits of the shortest distances and most favorable wind patterns. Selection of a particular habitat may occur once migrants settle in an area and may involve intrinsic factors such as characteristics of that vegetation type or habitat (for review see: Hutto 1985a and Moore and others 1995). Physical structure of the habitat, including plant species composition and foliage density, may influence how birds move through the habitat, see and capture prey, and may determine how susceptible

Table 2—Comparisons, between habitats at a different year and season, of relative abundance of arthropods and an index of arthropod abundance adjusting for shrub density. ANOVA results using log-transformed data. Duncan groupings provide comparisons of each habitat (C = Cottonwood, S = Salt Cedar, W = Willow). Letters not underscored by the same line are significantly different. Asterisks denote that significance ($P < 0.05$) remains and ns denotes its removal after a sequential bonferroni adjustment.

		Arthropod numbers/trap		Arthropod-Veg Index ^a	
	N = no. weeks	ANOVA P value	Duncan Groups: High mean to Low mean	ANOVA P value	Duncan Groups: High mean to low mean
All individuals					
Spring 1996	3	0.0001	W C S	0.0001	W S C
Fall 1996	5	0.0001	C W S	0.0001	W S C
Spring 1997	5	0.001	W C S	0.0004	W S C
Fall 1997	10	0.014	W S C	0.0001	S W C
Spring 1996					
		Six top ranking Orders (abundance of individuals)			
Beetles		0.039ns			
Flies		0.001*	W C S		
True Bugs		0.0005*	W S C		
Plant Bugs		0.068			
Wasps, etc.		0.002*	W C S		
Thrips		0.237			
Fall 1996					
		Six top ranking Orders (abundance of individuals)			
Beetles		0.62			
Flies		0.0002*	C W S		
True Bugs		0.278			
Plant Bugs		0.046ns			
Wasps, etc.		0.03ns			
Thrips		0.301			
Spring 1997					
		Six top ranking Orders (abundance of individuals)			
Beetles		0.002*	C W S		
Flies		0.001*	W C S		
True Bugs		0.552			
Plant Bugs		0.012*	W C S		
Wasps, etc.		0.08			
Thrips		0.353			
Fall 1997					
		Six top ranking Orders (abundance of individuals)			
Beetles		0.0001*	C W S		
Flies		0.0001*	W C S		
True Bugs		0.0001*	W S C		
Plant Bugs		0.009*	W S C		
Wasps, etc.		0.0001*	W C S		
Thrips		0.759			

^aArthropod-veg index = (number arthropod individuals/trap)* number shrub stems.

migrants are to predation (Robinson and Holmes 1982, 1984). Several studies indicate a relationship exists between food availability and avian selection of different habitats (reviewed in Moore and others 1995).

We examined measures of arthropod availability of cottonwood habitat, stands of willow and stands of exotic saltcedar. We found a difference among arthropod orders and their abundance among vegetation types. Typically, saltcedar harbored fewer total arthropods, particularly flies, compared to the cottonwood understory, and willow stands. When we extrapolated from numbers of arthropods caught on traps to what might be available on the vegetation by using a shrub density index, we instead found fewer

arthropods in the cottonwood midstory. This pattern might be explained by the fact that the cottonwood midstory, a large portion of which is saltcedar, is less dense than that of the monotypic saltcedar stand. In the future we plan to include vegetation species diversity and spatial aspects of vegetation to refine the relationship of arthropods to our vegetation types.

Sudbrook (1993) stated that arthropod populations on individual saltcedar plants fluctuate more in saltcedar monocultures than in mosaics of native vegetation. Those fluctuations may have negative impacts on wildlife that feed on arthropods. Contrary to what several other authors have reported (Cohen and others 1978 and Crawford and others

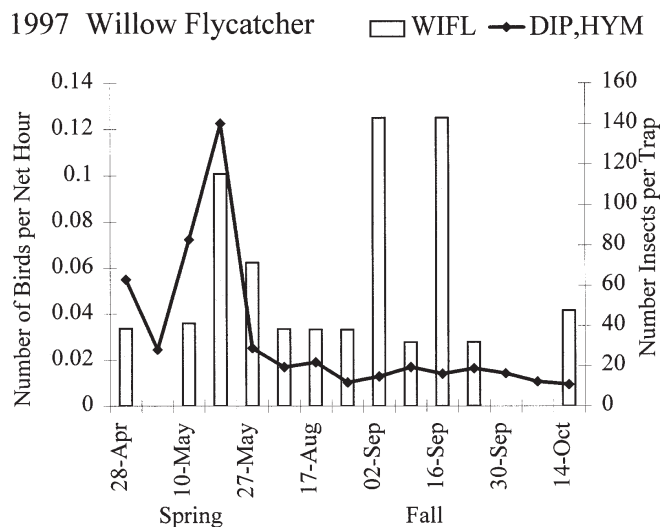


Figure 2—The relationship of Willow Flycatchers with that of aerial insects (Orders: Dip=Diptera, Hym=Hymenoptera) over time in 1997

1993), Mund-Meyerson and others (in Mund-Meyerson, 1998) report that arthropod density on saltcedar, based on fogging tree canopies, was not significantly different from cottonwood trees over most of the breeding season of migrant birds (May, June, and August samples). Our arthropod sampling in cottonwood habitat included only midstory trees and shrubs: saltcedar, Russian olive, and cottonwood. In order to evaluate possible migrant bird selection of exotic and native habitats during their migration, we need to examine more components of each habitat that may influence prey availability. These elements would include arthropod abundance and diversity in relation to both overstory and understory layers of a habitat (structural complexity), plant or arthropod species diversity of a habitat, and vegetation density. These factors may influence numbers of arthropods as well as their accessibility to avian predators. We will also incorporate information on foraging behaviors within our habitat designations in order to aid our evaluation and interpretation of vegetation use.

Our data suggest that migrating Wilson's Warblers (WIWA) and, perhaps, Willow Flycatchers (WIFL) respond to variation in arthropod abundance over time, especially during spring migration. There was an association of WIWA capture rates with both aerial and foliage insects over time. WIWA capture rates were associated with aerial insects in the willows in 1997. The association of WIFL capture rates with aerial insects was weak. Future analyses will examine the correlation of bird capture rates to those of arthropods on a net-to-trap basis. After completing our identification of glue-board arthropods for 1996 and sampling from 1998, we will have a more comprehensive data set from which to evaluate bird-arthropod associations in each of our habitat categories.

Depending on the migrant species, different taxa of arthropods may determine avian vegetation use. Our future analyses will include the examination of different families of arthropods and their association to migrant capture rates within each vegetation type. Raley and Anderson (1990)

found, for example, that riparian birds, one of which was the WIWA, selected arthropod prey disproportionately to availability in willow. They also found that very small arthropods were consistently underrepresented in WIWA diets. We found an association with insect abundance and WIWA in willow and hypothesize that this association may be in response to a similar temporal change in abundance of small dipterans such as gnats and chironomids. We need to examine data on avian prey-foraging behavior and prey selection within each vegetation type to better understand possible factors underlying vegetation and habitat use.

One school of thought suggests that food is only loosely exploited and is not important in determining bird species abundance (Wiens 1981); one might only expect a close association between bird population densities and food resource levels during times of resource shortages (Wiens 1977). However, Hutto (1985b) found that insectivorous migratory bird densities matched insect densities across habitats within a season and across seasons within a habitat during years with normal rainfall and thus probably not at a time of resource stress. We speculate that migrant birds at

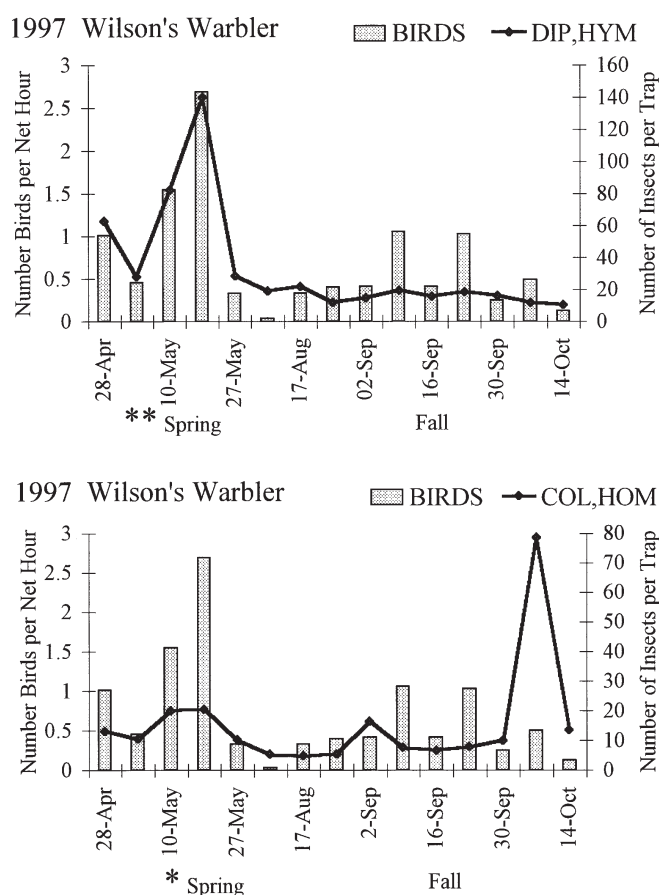


Figure 3—The relationship of Wilson's Warbler with that of aerial insects (Orders: Dip=Diptera, Hym=Hymenoptera) and foliage insects (Orders: Col=Coleoptera, Hom=Homoptera) over time in 1997. Asterisks denote a significant (*P=0.04, **P=0.0001) association between bird abundance and aerial insect abundance in spring.

Bosque del Apache Wildlife Refuge may have been resource-stressed on a large scale, in relation to arthropod numbers, in 1997. Fires in the summer of 1996 reduced a large proportion of riparian habitat at the refuge (J. Taylor, pers. comm.) and consequently would have reduced larger-scale availability of foraging habitat and arthropod prey. Capture rates of birds netted at the same sites have decreased during the two years following the fire (J. Kelly, pers. obs.). Weekly relative abundances of arthropods trapped on glue-boards were lower in 1997 than in 1996 (L. DeLay, pers. obs.). Perhaps less available foraging habitat caused migrating insectivores to disperse over a larger area in search of insect prey, and those stopping over at our sites were more responsive to differences in arthropod abundances. It has been suggested that migrants assess alternative habitats during an initial exploratory phase shortly after arrival (Moore and others 1990) and possible cues to prey availability may be feeding activity or high numbers of other migrant birds in the vegetation (Moore and others 1995). Perhaps, there were sufficient numbers of WIWA arriving weekly in our netting area during spring to respond to greater concentrations of other WIWA feeding in willow vegetation. Even though WIFL capture rates were greatest in willow (Kelly and others 1997), their relatively few numbers may be an insufficient cue to feeding activity.

Acknowledgments

We thank J. Taylor, P. Norton and the staff of Bosque del Apache National Wildlife Refuge for access, housing, and assistance with our migratory bird studies. We thank Wang Yong for assistance in developing the bird and arthropod sampling methods. We thank our crew leader, D. Hawksworth, and crew members for work and data entry for 1996 and 1997: S. Allerton, L. Balin, G. Bodner, M. Connolly, C. Mandras, and B. Rasch. We also thank Earthwatch International for supplying us with a volunteer workforce in 1997.

References

- Cohen, D.R., R.D. Ohmart, and B.W. Anderson. 1978. Avian population responses to saltcedar along the lower Colorado river. USDA Forest Service General Technical Report WO-12:371-382.
- Crawford, C.S., A.C. Cully, R. Leutheuser, M.S. Sifuentes, L.H. White, and J.P. Wilber. 1993. Middle Rio Grande ecosystems: Bosque biological management plan. US Fish and Wildlife Service, District 2, Albuquerque, NM.
- Hutto, R.L. 1985a. Habitat selection by nonbreeding, migratory land birds. In M. Cody, ed., *Habitat Selection in Birds*. Academic Press, New York.
- Hutto, R.L. 1985b. Seasonal changes in the habitat distribution of transient insectivorous birds in southeastern Arizona: competition mediated? *Auk* 102: 120-132.
- Finch, D.M., G.L. Wolters, W. Yong, and M.J. Mund. 1995. Plants, arthropods, and birds of the Rio Grande. In D.M. Finch and J.A. Tainter, technical eds., *Ecology, Diversity, and Sustainability of the Middle Rio Grande Basin*. USDA Forest Service General Technical Report 268:133-164.
- Kelly, J.K., D.M. Finch, and M.D. Means. 1997. Annual report on bird migration along the low flow conveyance channel in the Bosque del Apache NWR. Prepared for: The Bureau of Reclamation and The Bosque del Apache NWR.
- Mund-Meyerson, M.J. 1998. Arthropod abundance and composition on native vs. exotic vegetation in the Middle Rio Grande riparian forest as related to avian foraging. Master's Thesis. Department of Biology, The University of New Mexico, Albuquerque, NM.
- Moore, F.R., P. Kerlinger, and T.R. Simons. 1990. Stopover on a Gulf coast barrier island by spring trans-Gulf migrants. *Wilson Bulletin* 102: 487-500.
- Moore, F.R., S.A. Gauthreaux, P. Kerlinger, and T.R. Simons. 1995. Habitat requirements during migration: important link in conservation. In T.E. Martin and D.M. Finch, eds., *Ecology and Management of Neotropical Migratory Birds: a synthesis and review of critical issues*. Oxford Univ. Press.
- Ohmart, R.D. 1994. The effects of human-induced changes on the avifauna of western riparian habitats. *Studies in Avian Biology* 15:273-285.
- Raley, C.M. and S.H. Anderson. 1990. Availability and use of arthropod food resources by Wilson's Warblers and Lincoln's Sparrows in southeastern Wyoming. *Condor* 92:141-150.
- Rice, W. 1989. Analyzing tables of statistical tests. *Evolution* 43: 223-225.
- Robinson, S.K. and R.T. Holmes. 1982. Foraging behavior of forest birds: the relationship among search tactics, diet, and habitat structure. *Ecology* 63: 1918-1931.
- Robinson, S.K. and R.T. Holmes. 1984. Effect of plant species and foliage structure on the foraging behavior of forest birds. *Auk* 101: 672-684.
- SAS Institute. 1995. *Statistical Analysis Systems*, version 7. SAS Institute Inc. Cary, North Carolina.
- SPSS Inc. 1994. *SPSS/PC+*. Marija J. Norusis/SPSS Inc. Chicago, Illinois.
- Sudbrock, A. 1993. Tamarisk Control I. Fighting back: An overview of the invasion, and a low-impact way of fighting it. *Restoration and Management Notes* 11(1): 31-34.
- Whitney, J.C. 1996. The Middle Rio Grande: Its ecology and management. Pp. 4-21 In D. Shaw and D.M. Finch, tech eds., *Desired Future Conditions for Southwest Riparian Ecosystems: Bringing interests and concerns together*. General Technical Report RM-GTR-272. Rocky Mountain Experiment Station, Fort Collins, CO.
- Wiens, J.A. 1977. On competition and variable environments. *American Scientist* 65: 590-597.
- Wiens, J.A. 1981. Scale problems in avian censusing. In C.J. Ralph and J.M. Scott, eds., *Estimating the Numbers of Terrestrial Birds*. *Studies in Avian Biology* No.6.

Use of Saltcedar Vegetation by Landbirds Migrating Through the Bosque Del Apache National Wildlife Refuge

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Abstract—We compared diversity, abundance and energetic condition of migrant landbirds captured in four different vegetation types in the Bosque del Apache National Wildlife Refuge. We found lower species diversity among migrants caught in exotic saltcedar vegetation than in native willow or cottonwood. In general, Migrants were most abundant in agricultural edge and least abundant in cottonwood. There were no consistent patterns in energetic condition of common species among vegetation types. Ninety percent of statistical tests for variation in mass and fat score among vegetation types showed no significant difference. The few significant tests indicated that (1) Chipping Sparrows caught in saltcedar tended to be in poorer energetic condition than those caught in other vegetative types; (2) Ruby-crowned Kinglets captured in saltcedar tended to be in better energetic condition than those in other vegetative types; (3) The relationship between energetic condition of Wilson's Warbler's and vegetation type varied with year and season. The mixed evidence we report on the effects of exotic saltcedar on migrant birds parallels the existing literature on this topic. It is important to consider the configuration of vegetation types on the landscape when evaluating the effects of saltcedar on migrant birds.

Riparian vegetation that comprises the bosque of the Middle Rio Grande Valley is an important habitat component for both resident and migrant birds (Finch and Yong *in press*, Yong and others *in press*). Large numbers of en-route migrants use these riparian areas as stopover habitat and they likely represent a critical resource for successful migration (Farley and others 1994, Wauer 1977). The bosque was historically dominated by cottonwood-willow vegetative associations, but the abundance of these plants has been declining due to changes in the hydrograph of the Rio Grande and the invasion of saltcedar (*Tamarix ramosissima*; Howe and Knopf 1988). Saltcedar has become a dominant component of lowland desert riparian communities of the Southwest (Hunter and others 1988). In addition to the obvious effects of saltcedar on native plant communities, there is also concern over its effects on the quality of riparian habitat for birds and other animals.

One of the primary concerns has been the potential loss of biodiversity that could result if many bird species cannot sustain themselves in saltcedar dominated habitats. For

instance, over 240 species of birds are known to breed in the Middle Rio Grande Valley (Hink and Ohmart 1984). These species represent a large fraction (49 percent) of the 493 bird species that occur in New Mexico (Williams 1997). Furthermore, the concentration of endangered species in the Southwest is higher than in most other regions (Flather and others 1994, Reid 1998) and many of these species are riparian obligates. This loss of biodiversity may also have economic impacts. In New Mexico, 1.6 million people spent \$428 million on activities associated with watching wildlife in 1996 (USDI and USDOC 1997). Bird watching and hunting alone generated \$90 million in retail sales in New Mexico in 1991 (Inter. Assoc. Fish. & Wildl. Agencies 1992). So, there is substantial commerce that is derived from game and non-game wildlife in New Mexico. Thus, saltcedar has the potential to negatively impact both the biodiversity of New Mexico's fauna and the commerce that it supports.

For these reasons, there have been a number of studies on the effects of saltcedar on bird communities in the southwestern U.S. (Anderson and others 1977, Carothers 1974, Ellis 1995, Hunter and others 1985, Hunter and others 1988). The majority of these studies have found mixed results relative to the impact of saltcedar on bird communities. Interestingly, nearly all of these studies are based on community metrics and use point counts or other visual surveys as the primary means of assessing the response of birds to vegetation structure. While the results we report here are also derived from a community approach, our study differs from previous work in that we use data from mist nets to assess the relationship between vegetation structure and migrant diversity, abundance, and energetic condition. We reasoned that if saltcedar was poor migrant habitat, then we should catch fewer total number of birds of fewer species in this vegetation and these birds should be in poorer energetic condition than those caught in native willow (*Salix* spp.) and cottonwood (*Populus* spp.) vegetation.

Methods

Our study area was at the north edge of the Bosque del Apache National Wildlife Refuge (N33°48', W106°52'; hereafter Bosque del Apache). This mist-net area was chosen because it contained a diversity of vegetation types in close proximity. That is, all nets were within a 1 km radius circle of the banding station. We used mist nets (12 m x 2.6 m, 30 or 36 mm mesh) to capture spring and fall migrants at the Bosque del Apache. We placed nets in four vegetation types. These types were: (1) cottonwood (*Populus fremontii*) forests with mixed native and exotic understory (14 nets in 1996 and 7 nets in 1997); (2) saltcedar monocultures (5 nets in 1996 and 7 nets in 1997); (3) willow strips along irrigation canals (18 nets in both years); and along an agricultural edge

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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(3 nets in both years). Agricultural edge nets were located in strips of cottonwood (2 nets) and in fourwing saltbush (*Atriplex canescens*; 1 net). Nets were operated from mid April to early June (referred to hereafter as spring) and from early August until early November (referred to hereafter as fall) each year. Nets were operated 5 days per week, and were opened 15 minutes prior to sunrise for about 6 h/d except during inclement weather. Nets were checked at 20-30 minute intervals. Each bird captured was marked with a uniquely numbered aluminum leg band. The mass, morphological features (for example, unflattened wing chord, tarsus, and culmen lengths) and the fat condition of each bird were measured. Fat condition was scored on an integer scale from zero to six (Helms and Drury 1960).

To compare the diversity of birds captured among vegetation types we used rarefaction curves (James and Rathbun 1981, Ludwig and Reynolds 1988). These curves represent the number of species that we would expect to catch in any sample of individuals. These expected values were generated from the relative abundance of all species in the capture data. Comparison among rarefaction curves is limited by the number of individuals captured in the sparsest subsample (James and Rathbun 1981). For this reason, we compared expected number of species in samples of 100 individuals from each vegetation type.

To compare abundance of migrants among vegetation types we calculated capture rates as number of birds/1000 net h. A single mist net operated for 1 hour equals one net hour. We calculated capture rates for: (1) all captures; (2) for the 5 most common families; and (3) for seven individual species that represented the most common families and had

relatively large numbers of captures in saltcedar. These species were Brewer's Sparrow (*Spizella breweri*), Chipping Sparrow (*Spizella passerina*), Dark-eyed Junco (*Junco hyemalis*), Dusky Flycatcher (*Empidonax oberholseri*), Ruby Crowned Kinglet (*Regulus calendula*), White-crowned Sparrow (*Zonotrichia leucophrys*), Wilson's Warblers (*Wilsonia pusilla*). We also compare mass and fat score among vegetation types for these seven species. We used Kruskal-Wallis tests to compare capture rates, mass, and fat scores among vegetation types. We conducted separate tests for each year and season.

Results

We operated mist nets for a total of 41,652 net hrs. Effort was evenly divided between the two years; 21,082 net hrs (51 percent) in 1996 and 20,570 net hrs (49 percent) in 1997. More effort was used to catch birds in the fall (26,023 net hrs; 63 percent) than in the spring (15,629 net hrs; 37 percent). We captured a total of 5,466 birds in the two years. Unlike our effort, these captures were not evenly divided between the two years. Many more birds were captured in 1996 (3,732 individuals; 68 percent) than in 1997 (1,734 individuals, 32 percent). While we also captured more individuals in the fall (3,184 individuals; 58 percent) than in the spring (2,282 individuals; 42 percent), this pattern parallels the difference in effort between the seasons.

We captured individuals of 118 species that represented 25 families (table 1). Five families accounted for 80 percent of captures. These were: Warblers (Parulidae; 2,234

Table 1—Number of captures for 118 species of birds mist-netted at the Bosque del Apache during 1996 and 1997.

Common name	Scientific name	1996			1997			Grand total
		Spring	Fall	Total	Spring	Fall	Total	
HAWKS								
Northern Harrier	<i>Circus cyaneus</i>	0	1	0	0	0	0	1
Sharp-shinned Hawk	<i>Accipiter striatus</i>	0	0	0	1	0	1	1
Coopers Hawk	<i>Accipiter cooperii</i>	0	1	1	0	0	0	1
DOVES								
Mourning Dove	<i>Zenaida macroura</i>	0	0	0	1	3	4	4
White-winged Dove	<i>Zenaida asiatica</i>	0	0	0	1	0	1	1
Common Ground Dove	<i>Columbina passerina</i>	0	0	0	1	0	1	1
CUCKOOS								
Greater Roadrunner	<i>Geococcyx californianus</i>	0	1	1	2	1	3	4
Yellow-billed Cuckoo	<i>Coccyzus americanus</i>	2	2	4	0	2	2	6
HUMMINGBIRDS*								
Black-chinned Hummingbird	<i>Archilochus alexandri</i>	42	10	52	67	27	94	146
Calliope Hummingbird	<i>Stellula calliope</i>	0	0	0	0	1	1	1
Broad-tailed Hummingbird	<i>Selasphorus platycercus</i>	5	1	6	2	0	2	8
Rufous Hummingbird	<i>Selasphorus rufus</i>	0	6	6	0	3	3	9
KINGFISHERS								
Belted Kingfisher	<i>Ceryle alcyon</i>	0	0	0	0	2	2	2
WOODPECKERS								
Hairy Woodpecker	<i>Picoides villosus</i>	1	0	1	1	0	1	2
Downy woodpecker	<i>Picoides pubescens</i>	0	0	0	0	1	1	1
Ladder-backed Woodpecker	<i>Picoides scalaris</i>	0	0	0	1	0	1	1
Red-naped Sapsucker	<i>Sphyrapicus nuchalis</i>	0	2	2	0	1	1	3
Williamson's Sapsucker	<i>Sphyrapicus thyroideus</i>	0	1	1	0	0	0	1
Northern Flicker	<i>Colaptes auratus</i>	0	4	4	0	2	2	6

(con.)

Table 1 (Con.)

Common name	Scientific name	1996			1997			Grand total
		Spring	Fall	Total	Spring	Fall	Total	
FLYCATCHERS								
Western Kingbird	<i>Tyrannus verticalis</i>	0	1	1	1	1	2	3
Brown-crested Flycatcher	<i>Myiarchus tyrannulus</i>	0	1	1	0	0	0	1
Ash-throated Flycatcher	<i>Myiarchus cinerascens</i>	13	0	13	12	0	12	25
Say's Pheobe	<i>Sayornis saya</i>	1	1	2	0	0	0	2
Black Pheobe	<i>Sayornis nigricans</i>	8	1	9	9	2	11	20
Western Wood-pewee	<i>Contopus sordidulus</i>	20	20	40	7	3	10	50
Western Flycatcher	<i>Empidonax difficilis</i>	5	10	15	1	4	5	20
Willow Flycatcher	<i>Empidonax traillii</i>	27	23	50	29	12	41	91
Hammond's Flycatcher	<i>Empidonax hammondii</i>	9	5	14	0	0	0	14
Dusky Flycatcher	<i>Empidonax oberholseri</i>	102	21	123	31	7	38	161
Gray Flaycatcher	<i>Empidonax wrightii</i>	10	2	12	1	2	3	15
VIREOS								
Red-eyed Vireo	<i>Vireo olivaceus</i>	1	0	1	0	0	0	1
Warbling Vireo	<i>Vireo gilvus</i>	45	46	91	12	18	30	121
Yellow-throated Vireo	<i>Vireo flavifrons</i>	1	0	1	0	0	0	1
Solitary Vireo	<i>Vireo solitarius</i>	13	5	18	2	1	3	21
Gray Vireo	<i>Vireo vicinior</i>	1	0	1	0	0	0	1
JAYS								
Western Scrub Jay	<i>Aphelocoma californica</i>	0	0	0	0	1	1	1
SWALLOWS								
Barn Swallow	<i>Hirundo rustica</i>	7	5	12	4	2	6	18
Northern Rough-winged Swallow	<i>Stelgidopteryx serripennis</i>	3	0	3	6	0	6	9
CHICKADEES								
Mountain Chickadee	<i>Poecile gambeli</i>	1	1	2	0	0	0	2
VERDINS								
Verdin	<i>Auriparus flaviceps</i>	0	2	2	0	0	0	2
BUSHTITS								
Common Bushtit	<i>Psaltriparus minimus</i>	0	1	1	0	19	19	20
NUTHATCHES								
White-breasted Nuthatch	<i>Sitta carolinensis</i>	1	0	1	0	0	0	1
Red-breasted Nuthatch	<i>Sitta canadensis</i>	0	3	3	0	0	0	3
CREEPERS								
Brown Creeper	<i>Certhia americana</i>	0	11	11	0	0	0	11
WRENS								
Cactus Wren	<i>Campylorhynchus brunneicapillus</i>	0	0	0	0	0	1	1
Rock Wren	<i>Salpinctes obsoletus</i>	0	1	1	0	0	0	1
Carolina Wren	<i>Thryothorus ludovicianus</i>	1	0	1	0	0	0	1
Bewick's Wren	<i>Thyromanes bewickii</i>	15	24	39	13	22	35	74
House Wren	<i>Troglodytes aedon</i>	33	11	44	7	2	9	53
Winter Wren	<i>Troglodytes troglodytes</i>	0	1	1	0	0	0	1
Marsh Wren	<i>Cistothorus palustris</i>	1	2	3	0	0	0	3
GNATCATCHERS								
Blue-gray gnatcatcher	<i>Polioptila caerulea</i>	3	0	3	2	0	2	5
THRUSHES								
Townsend's Solitaire	<i>Myadestes townsendi</i>	1	1	2	1	0	1	3
Swainson's Thrush	<i>Catharus ustulatus</i>	3	2	5	1	0	1	6
Hermit Thrush	<i>Catharus guttatus</i>	15	9	24	3	1	4	28
American Robin	<i>Turdus migratorius</i>	13	2	15	11	0	11	26
Ruby-crowned Kinglet	<i>Regulus calendula</i>	25	132	157	30	115	145	302
MIMIC THRUSHES								
Northern Mockingbird	<i>Mimus polyglottos</i>	6	0	6	1	0	1	7
Gray Catbird	<i>Dumetella carolinensis</i>	2	3	5	0	0	0	5
WOOD WARBLERS								
Black and White Warbler	<i>Mniotilta varia</i>	1	2	3	0	0	0	3
Prothonotary Warbler	<i>Protonotaria citrea</i>	0	2	2	0	1	1	3
Blue-winged Warbler	<i>Vermivora pinus</i>	1	0	1	1	0	1	2
Golden-winged Warbler	<i>Vermivora chrysoptera</i>	0	0	0	2	0	2	2

(con.)

Table 1 (Con.)

Common name	Scientific name	1996			1997			Grand total
		Spring	Fall	Total	Spring	Fall	Total	
WOOD WARBLERS (Con.)								
Lucy's warbler	<i>Vermivora luciae</i>	1	0	1	2	0	2	3
Virginia's Warbler	<i>Vermivora virginiae</i>	18	34	52	5	12	17	69
Nashville Warbler	<i>Vermivora ruficapilla</i>	3	0	3	0	1	1	4
Orange-crowned Warbler	<i>Vermivora celata</i>	32	37	69	10	30	40	109
Yellow Warbler	<i>Dendroica petechia</i>	44	77	121	48	34	82	203
Black-throated Blue Warbler	<i>Dendroica caerulescens</i>	0	1	1	0	0	0	1
Yellow-rumped Warbler	<i>Dendroica coronata</i>	53	39	92	9	7	16	108
Magnolia Warbler	<i>Dendroica magnolia</i>	2	0	2	0	0	0	2
Chestnut-sided Warbler	<i>Dendroica pensylvanica</i>	2	0	2	0	0	0	2
Bay-breasted Warbler	<i>Dendroica castanea</i>	0	0	0	1	0	1	1
Black-throated Gray Warbler	<i>Dendroica nigrescens</i>	1	0	1	0	1	1	2
Townsend's Warbler	<i>Dendroica townsendi</i>	2	1	3	0	2	2	5
Prairie Warbler	<i>Dendroica discolor</i>	1	0	1	0	0	0	1
Ovenbird	<i>Seiurus motacilla</i>	4	0	4	0	0	0	4
Northern Waterthrush	<i>Seiurus noveboracensis</i>	0	8	8	0	4	4	12
Kentucky Warbler	<i>Oporornis formosus</i>	1	0	1	0	0	0	1
MacGillivray's Warbler	<i>Opornis tolmiei</i>	234	62	296	30	41	71	367
Common Yellowthroat	<i>Geothlypis trichas</i>	63	19	82	45	21	66	148
Yellow-breasted Chat	<i>Icteria virens</i>	26	4	30	10	8	18	48
Hooded Warbler	<i>Wilsonia citrina</i>	2	0	2	0	0	0	2
Wilson's Warbler	<i>Wilsonia pusilla</i>	348	380	728	124	294	418	1146
Canada Warbler	<i>Wilsonia canadensis</i>	1	0	1	0	0	0	1
American Redstart	<i>Setophaga ruticilla</i>	1	1	2	1	1	2	4
TANAGERS								
Western Tanager	<i>Piranga ludoviciana</i>	4	31	35	2	3	5	40
Hepatic Tanager	<i>Piranga flava</i>	0	2	2	0	0	0	2
Summer Tanager	<i>Piranga rubra</i>	13	37	50	6	10	16	66
SPARROWS								
Vesper Sparrow	<i>Poocetes gramineus</i>	2	1	3	1	2	3	6
Savannah Sparrow	<i>Passerculus sandwichensis</i>	0	4	4	1	8	9	13
Lark Sparrow	<i>Chondestes grammacus</i>	4	7	11	0	8	8	19
Harris' Sparrow	<i>Zonotrichia querula</i>	0	0	0	1	0	1	1
White-crowned Sparrow	<i>Zonotrichia leucophrys</i>	77	211	288	132	60	192	480
White-throated Sparrow	<i>Zonotrichia albicollis</i>	0	2	2	0	0	0	2
Chipping Sparrow	<i>Spizella passerina</i>	33	265	298	9	17	26	324
Clay-colored Sparrow	<i>Spizella padilla</i>	0	0	0	0	11	11	11
Brewer's Sparrow	<i>Spizella breweri</i>	57	32	79	6	33	39	118
Dark-eyed Junco	<i>Junco hyemalis</i>	40	133	173	9	29	38	211
Black-throated Sparrow	<i>Amphispiza bilineata</i>	1	0	1	0	1	1	2
Sage Sparrow	<i>Amphispiza belli</i>	0	0	0	0	1	1	1
Song Sparrow	<i>Melospiza melodia</i>	3	115	118	2	28	30	148
Lincoln's Sparrow	<i>Melospiza lincolni</i>	14	125	139	4	34	38	177
Swamp Sparrow	<i>Melospiza georgiana</i>	0	1	1	0	0	0	1
Fox Sparrow	<i>Passerella iliaca</i>	0	2	2	0	0	0	2
Spotted Towhee	<i>Pipilo maculatus</i>	22	37	59	10	19	29	98
Green-tailed Towhee	<i>Pipilo chlorurus</i>	18	12	30	6	8	14	44
Canyon Towhee	<i>Pipilo fuscus</i>	1	0	1	0	1	1	2
GROSBEAKS & BUNTINGS								
Pyrrhuloxia	<i>Cardinalis sinuatus</i>	0	1	1	0	0	0	1
Black-headed Grosbeak	<i>Pheucticus melanocephalus</i>	31	25	56	25	3	28	84
Blue Grosbeak	<i>Guiraca caerulea</i>	25	61	86	14	76	90	176
Indigo Bunting	<i>Passerina cyanea</i>	7	4	11	8	7	15	26
Lazuli Bunting	<i>Passerina amoena</i>	5	31	36	2	11	13	49
Painted Bunting	<i>Passerina ciris</i>	0	2	2	0	0	0	2
BLACKBIRDS								
Brown-headed Cowbird	<i>Molothrus ater</i>	8	0	8	21	0	21	29
Red-winged Blackbird	<i>Agelaius phoeniceus</i>	1	2	3	0	2	2	5
Northern Oriole	<i>Icterus galbula</i>	5	3	8	3	0	3	11
Common Grackle	<i>Quiscalus quiscula</i>	0	0	0	1	0	1	1
Great-tailed Grackle	<i>Quiscalus mexicanus</i>	0	0	0	3	0	3	3
FINCHES								
House Finch	<i>Carpodacus mexicanus</i>	15	1	16	7	1	8	24
American Goldfish	<i>Carduelis tristis</i>	2	1	3	1	0	1	4
Lesser Goldfinch	<i>Carduelis psaltria</i>	6	12	18	0	2	2	20

*Note that hummingbirds were not banded, So some of the captured birds may be repeats.

individuals; 41 percent), Sparrows (Emberizidae; 1,572 individuals; 29 percent of all captures), Flycatchers (Tyrannidae; 399 individuals; 7 percent), Thrushes (Turdidae; 368 individuals; 7 percent), and Grosbeaks (331 individuals; 6 percent). The remaining 20 families accounted for only 20 percent of all captures (562 individuals). We caught >200 individuals of seven species: Wilson's Warbler, MacGillivray's Warbler (*Oporornis philadelphia*), Yellow Warbler (*Dendroica petechia*), White-crowned Sparrow, Chipping Sparrow, Dark-eyed Junco, and Ruby Crowned Kinglet.

Rarefaction curves indicate that the diversity of migrants captured in saltcedar was lower than that captured in native cottonwood and willow in 3 of the 4 seasons examined (fig. 1); the exception was spring 1997. There was also a tendency for diversity of birds captured to be lower in agriculture edge than in native bosque vegetation.

Capture rates were higher in all vegetation types during 1996 than in 1997 (fig. 2). There was significant variation in capture rates among vegetation types in spring ($\chi^2 = 27.8$, $df = 3$, $p < 0.001$) and fall ($\chi^2 = 6.3$, $df = 3$, $p < 0.1$) of 1996 and in fall 1997 ($\chi^2 = 6.9$, $df = 3$, $p < 0.08$), but this variation was not significant in spring 1997. Cottonwood had the lowest capture rate in both seasons of both years and saltcedar had the second lowest capture rate in both seasons of 1997 and

spring of 1996. Agricultural edge had the highest capture rates in both seasons of 1997 and in the fall of 1996. Significant variation in capture rates among vegetation types was also evident in some of the common families in some seasons (table 2).

Of the seven species examined, six showed significant variation in abundance among vegetation types in at least one sampling period (table 3). All four sparrows showed significant variation in capture rates in spring and fall 1996, but the only significant pattern among these species in 1997 was for Dark-eyed Juncos in the fall. Chipping, White-crowned, and Brewer's sparrows tended to be most abundant in the agricultural edge and least abundant in the cottonwood. Dark-eyed Juncos differed from the other sparrows by being most abundant in cottonwood and saltcedar. Wilson's Warblers tended to be most abundant in willow, but were also abundant in the agricultural edge in 1996 and in saltcedar in both falls. While, Ruby-crowned Kinglets tended to be most common in willow, there was no significant variation in their abundance among vegetation types in any season. Finally, Dusky Flycatchers tended to be most abundant in saltcedar, followed by willow (3 of 4 seasons). However, significant variation in capture rates of Dusky Flycatchers among vegetation types was evident only in spring

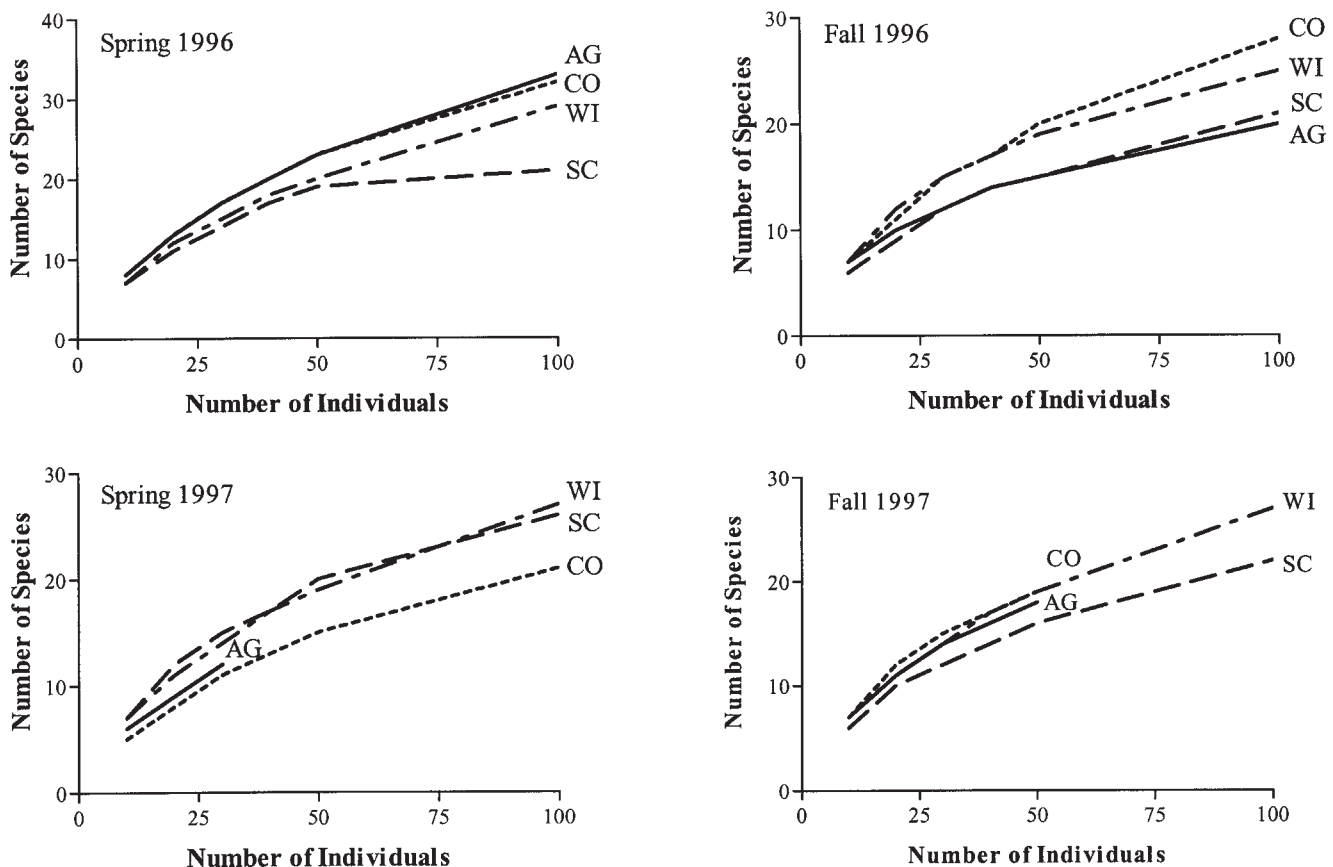


Figure 1—Rarefaction curves that describe how many migrating bird species we would expect to capture in a sample of individuals from vegetation types at the Bosque del Apache. The letters to the right of the curves indicate vegetation types (AG = agricultural edge, CO = cottonwood, SC = saltcedar, WI = willow). These curves indicate that diversity of migrants in saltcedar was generally lower than in willow or cottonwood habitat. Spring 1997 is the exception to this generality.

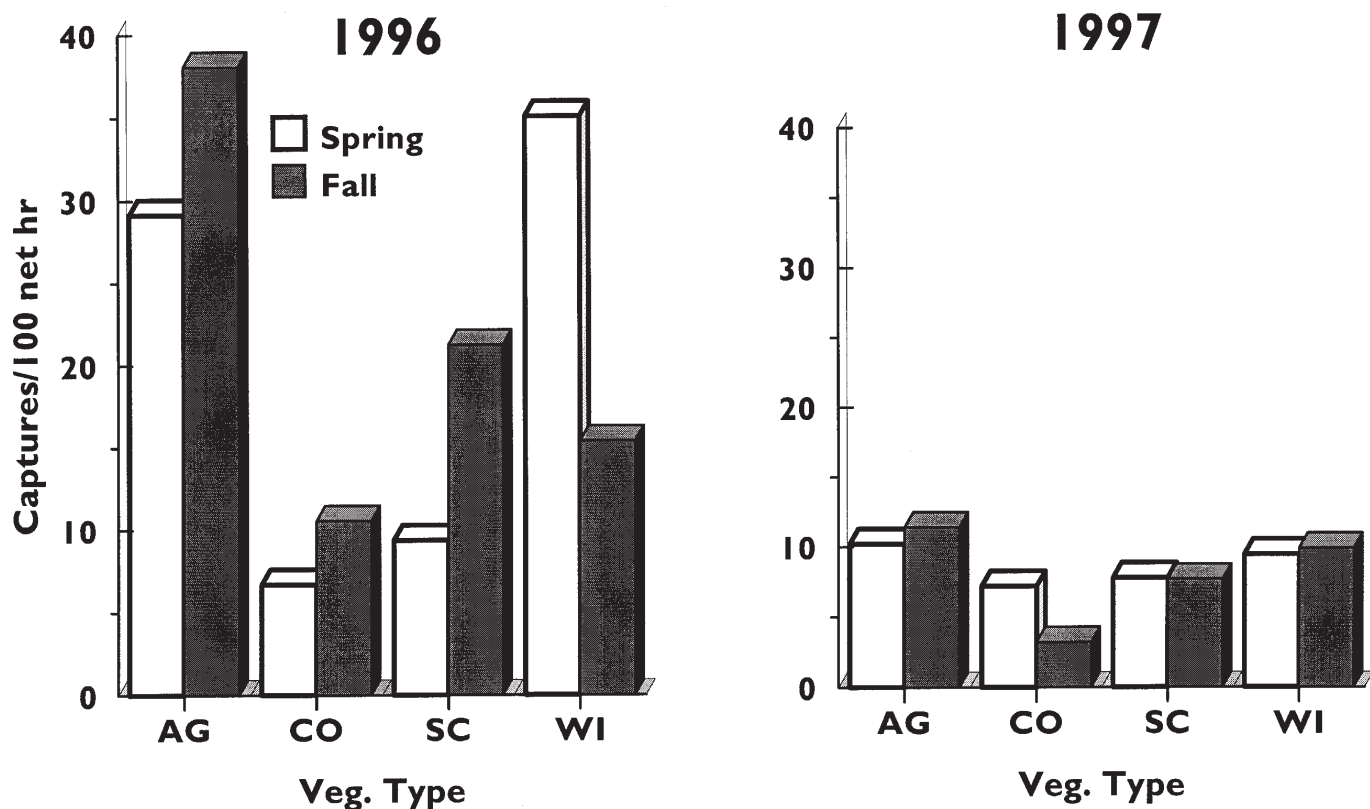


Figure 2—Capture rates/1000 net hours for en-route migrants in vegetation types at the Bosque del Apache. Vegetation types were agricultural edge (AG), cottonwood (CO), saltcedar (SC), and willow (WI). Note that (1) capture rates were higher in 1996 than in 1997; (2) agricultural edge tends to have the highest capture rates; and (3) cottonwood tends to have the lowest capture rates.

Table 2—Vegetation specific capture rates ($\bar{x} \pm SD$) for the five most common families of migrants in the Bosque del Apache of the Middle Rio Grande Valley. Differences among vegetation types were assessed with Kruskal-Wallis tests. Lines that are in boldface type had significant variation in capture rates among habitats.

Family	Year	Season	Vegetation type			
			AG	CO	SC	WI
Flycatcher	1996	Spring***	2.4 ± 0.7	0.9 ± 1.0	2.3 ± 0.5	4.0 ± 2.3
		Fall	0.8 ± 0.6	0.6 ± 0.4	1.2 ± 0.6	0.5 ± 0.5
	1997	Spring	0.7 ± 0.6	1.1 ± 0.7	1.9 ± 1.5	0.9 ± 0.8
		Fall	0.2 ± 0.3	0.2 ± 0.3	0.2 ± 0.2	0.7 ± 0.6
Thrush	1996	Spring	1.0 ± 0.9	0.9 ± 0.7	0.3 ± 0.3	0.6 ± 0.7
		Fall	1.2 ± 0.5	0.8 ± 0.6	0.9 ± 0.4	1.5 ± 1.5
	1997	Spring	1.4 ± 2.4	0.5 ± 0.5	0.4 ± 0.5	0.6 ± 1.0
		Fall	0.3 ± 0.3	0.5 ± 0.6	1.3 ± 0.9	1.0 ± 1.3
Warbler	1996	Spring***	9.9 ± 6.5	2.5 ± 2.0	3.3 ± 0.4	20.0 ± 17.0
		Fall	10.0 ± 13.0	3.8 ± 2.6	2.8 ± 2.4	5.9 ± 4.6
	1997	Spring	2.0 ± 3.0	2.5 ± 3.2	2.4 ± 1.9	4.8 ± 5.9
		Fall*	1.1 ± 0.5	0.7 ± 1.1	3.5 ± 3.3	5.1 ± 5.7
Sparrow	1996	Spring***	8.7 ± 3.4	1.2 ± 1.1	2.5 ± 1.2	4.8 ± 3.2
		Fall**	20.1 ± 17.8	2.3 ± 3.1	14.7 ± 4.5	5.7 ± 6.9
	1997	Spring	5.0 ± 4.3	1.5 ± 1.5	2.0 ± 1.5	1.3 ± 1.5
		Fall	6.1 ± 9.5	0.6 ± 0.5	2.1 ± 0.7	2.0 ± 1.7
Grosbeak	1996	Spring***	1.8 ± 0.8	0.3 ± 0.3	0.1 ± 0.3	1.6 ± 1.8
		Fall	4.8 ± 4.0	0.8 ± 0.9	0.4 ± 0.6	0.5 ± 0.9
	1997	Spring	0.2 ± 0.3	0.6 ± 0.3	0.5 ± 0.5	0.7 ± 0.8
		Fall*	3.1 ± 3.0	0.4 ± 0.4	0.1 ± 0.2	0.8 ± 1.1

* indicates $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 3—Mean captures per 1000 net-h (SD) by vegetation type for 7 species of landbirds that migrate through the Middle Rio Grande. Kruskal-Wallis tests were used to examine differences among vegetation types.

Species	Year	Season	Vegetation type				P<
			Ag. Edge	Cottonwood	Saltcedar	Willow	
Sparrows							
Chipping Sparrow	1996	Spring	5.9 (6.0)	0.9 (2.5)	3.2 (4.8)	7.9 (7.5)	0.02
		Fall	71.2 (84.9)	5.7 (13.7)	71.5 (34.1)	7.8 (12.2)	0.01
	1997	Spring	1.5 (2.7)	0.6 (1.7)	1.3 (3.4)	1.3 (3.1)	0.95
		Fall	1.8 (3.1)	0.0 (0.0)	1.9 (2.0)	1.5 (3.5)	0.20
White-crowned Sparrow	1996	Spring	32.5 (26.7)	1.9 (3.7)	0.0 (0.0)	16.3 (15.3)	0.01
		Fall	41.4 (59.3)	1.1 (1.9)	23.2 (16.8)	13.9 (20.2)	0.01
	1997	Spring	39.3 (34.3)	7.7 (13.0)	10.2 (9.8)	10.2 (13.4)	0.50
		Fall	21.7 (35.2)	1.2 (3.1)	3.5 (2.6)	5.3 (7.7)	0.30
Brewer's Sparrow	1996	Spring	10.3 (14.2)	1.2 (2.0)	16.3 (12.8)	8.8 (15.4)	0.05
		Fall	4.0 (3.4)	0.2 (0.8)	6.5 (8.8)	2.1 (2.7)	0.05
	1997	Spring	1.5 (2.6)	0.0 (0.0)	0.7 (1.8)	0.0 (0.0)	0.10
		Fall	3.6 (6.3)	0.0 (0.0)	3.9 (3.4)	2.9 (4.1)	0.07
Dark-eyed Junco	1996	Spring	22.2 (19.4)	5.3 (4.9)	2.2 (4.9)	2.1 (6.5)	0.02
		Fall	3.0 (3.0)	13.4 (15.2)	27.4 (15.7)	3.2 (4.3)	0.01
	1997	Spring	0.0 (0.0)	3.8 (8.3)	1.3 (2.2)	0.3 (1.1)	0.35
		Fall	0.9 (1.6)	2.3 (4.3)	6.5 (4.4)	0.8 (1.6)	0.01
Warblers							
Wilson's Warbler	1996	Spring	35.6 (35.6)	4.3 (10.6)	8.7 (8.3)	85.4 (105.5)	0.01
		Fall	65.2 (3.0)	29.2 (23.4)	18.4 (16.7)	25.3 (23.9)	0.90
	1997	Spring	4.5 (7.8)	14.2 (28.1)	12.2 (8.8)	20.1 (30.4)	0.15
		Fall	5.4 (2.7)	5.0 (6.9)	25.4 (25.2)	31.6 (40.8)	0.05
Thrushes							
Ruby-crowned Kinglet	1996	Spring	1.5 (2.6)	3.4 (4.3)	0.0 (0.0)	3.6 (4.7)	0.25
		Fall	10.9 (6.2)	5.5 (4.8)	7.1 (3.4)	14.5 (15.2)	0.10
	1997	Spring	0.0 (0.0)	3.2 (4.9)	2.5 (5.0)	5.3 (9.8)	0.35
		Fall	2.7 (2.7)	5.0 (6.1)	12.3 (8.6)	9.8 (13.2)	0.15
Flycatchers							
Dusky Flycatcher	1996	Spring	3.0 (2.6)	4.7 (6.2)	15.3 (7.2)	20.8 (11.3)	0.01
		Fall	1.0 (1.7)	1.1 (1.5)	4.2 (3.4)	1.4 (1.9)	0.15
	1997	Spring	1.5 (2.7)	3.2 (4.2)	10.3 (12.8)	2.3 (2.8)	0.40
		Fall	0.0 (0.0)	0.0 (0.0)	1.2 (1.4)	0.6 (1.8)	0.15

of 1996 when this species was most abundant in willow. It appears that differences in abundance among vegetation types were more evident in 1996 when most species were more abundant than in 1997.

We conducted a total of 80 Kruskal-Wallis tests to detect variation in mass and fat score among the seven common species; 40 test for variation in fat and 40 tests for variation in mass. Of these 80 tests, eight showed significant variation among vegetation types (two for variation in mass and six for variation in fat; table 4). In three of the eight significant tests, after-hatch-year Chipping Sparrows caught in saltcedar had lower mass or fat score than those caught in other vegetation types. This relatively strong indication that saltcedar was associated with poor Chipping Sparrow habitat was not evident in other species. The only other indication that saltcedar might be poor quality vegetation for migrants was that after-hatch year male Wilson's Warblers caught in saltcedar in Spring 1996 had lower fat scores than those caught in other vegetation types. This pattern is interesting because in the following year after-hatch year male Wilson's Warblers caught in saltcedar had higher fat scores than those caught in other vegetation types. Overall there were three instances in which birds caught in saltcedar had higher fat scores than those captured in other

vegetation types (two in Wilson's Warbler and one in Ruby-crowned Kinglets). Three of the seven species tested showed no significant variation in mass or fat score among vegetation types in either year or season.

Discussion

In general, migrants were more abundant in 1996 than in 1997. This pattern seems difficult to explain on the basis of changes in local habitat condition. That is, there was little change in the vegetation in our net area between years. There was a substantial fire in the Bosque del Apache NWR in 1996 that burned bosque habitats south of our netting area. It is possible that the loss of these nearby habitats affected captures in our net area, but we have no direct evidence of this effect. In addition, capture rates in 1997 were similar to those from 1994 and 1995 in this same area (D.M. Finch unpub data), which suggest that unusually high capture rates in 1996 are the phenomenon that requires explanation rather than the low capture rates of 1997.

Any likely explanation for annual variation in capture rates would have to include large scale weather patterns that affect both the condition of stopover habitats locally and regionally and the ability of migrants to get to those sites.

Table 4—Significant results of Kruskal-Wallis tests for variation in fat and mass among vegetation types in the Bosque del Apache National Wildlife Refuge. Number of tests conducted for each species is in parentheses following the species name. Age categories are after-hatch year (AHY), hatch-year (HY), and Unknown (UNK).

Species	Season	Year	Age	Sex	P-values ^a	
					Fat	Mass
Sparrows						
Chipping Sparrow (8)	Spring	1996	AHY	UNK	NS	0.05*
	Fall	1996	AHY	UNK	0.01*	0.03*
White-crowned Sparrow (12)	Spring	1997	AHY	UNK	0.04	NS
Brewer's Sparrow (4)	—	—	—	—	—	—
Dark-eyed Junco (8)	—	—	—	—	—	—
Warblers						
Wilson's Warbler (32)	Spring	1996	AHY	Male	0.02+	NS
	Spring	1997	AHY	Male	0.03*	NS
	Fall	1996	HY	Female	0.01+	NS
Thrushes						
Ruby-crowned Kinglet (12)	Fall	1996	UNK	Female	0.01+	NS
Flycatchers						
Dusky Flycatcher (4)	—	—	—	—	—	—

^aAsterisks indicate where birds caught in saltcedar habitat had the lowest mass/fat score and Plus signs indicate where birds caught in saltcedar had the highest mass/fat score.

As we expected, we found evidence that migrants were less diverse in exotic saltcedar than in native cottonwood and willow. This pattern appeared to be more pronounced in 1996. It is possible that the larger distinction in diversity between saltcedar and native habitats in 1996 is related to the occurrence of rare eastern migrants. That is, in 1996 we captured a relatively large number of uncommon eastern migrants and we might expect that these migrants would be more familiar with wet deciduous habitats rather dry desert scrub habitats. If so, the affinity of these uncommon species for willow and cottonwood habitats could account for the pronounced difference in diversity between saltcedar and native vegetation types in 1996.

Contrary to our expectations, we found that migrant abundance tended to be greatest in agricultural edge areas and intermediate in both saltcedar and willow. Cottonwood tended to have the lowest abundance of migrants. Variation in abundance among vegetation types was generally greater in 1996 than in 1997. This pronounced variation in 1996 may have been related to the density of migrants. Increased numbers of migrants may have increased competition for resources and forced individuals to be more selective in the vegetation types that they occupied.

Another consideration for comparing capture rates among vegetation types is that our ability to sample vegetation types is related to their morphology. Because of the short stature of agricultural, willow, and saltcedar vegetation our sampling of these vegetation types is fairly uniform in contrast to cottonwood forests where our samples reflect largely just the understory avifauna. So, variation in capture rates among habitats may reflect sampling bias as well as the distribution of birds. In particular, the low capture rates in cottonwoods may be a reflection of sampling bias.

Our evidence on the effects of saltcedar on energetic condition of migrants was mixed. Chipping Sparrow energetic condition provided some evidence that saltcedar was a component of poor stopover habitat. Other species

(Dark-eyed Juncos, Brewer's sparrows, and Dusky Flycatchers) showed no variation among vegetation types. Wilson's Warbler was the only species for which evidence on the effects of saltcedar on energetic condition was conflicted. Finally, Ruby-crowned Kinglets provided evidence that at some times for some species, birds caught in saltcedar vegetation were in better energetic condition than those caught in native vegetation.

There are several potential causes for the general lack of consistent variation in energetic condition of migrants among vegetation types. For instance, perhaps there is no difference in the availability of arthropod food among vegetation types. This pattern would diminish the potential for variation in energetic condition of migrants among vegetation types. Evidence consistent with this explanation has been found by Mund-Meyerson and others. They found that, in general, the arthropod fauna of cottonwood, Russian olive, and saltcedar were similar and fairly stable during May through August in the Bosque del Apache NWR. In contrast to this evidence DeLay and others (this volume) show that in our net area there was significant variation in arthropod communities among vegetation types. Specifically there were fewer arthropods, primarily flies (diptera), in saltcedar than in the native vegetation types. Further, Delay and others (this volume) provide some evidence that migrants track the abundance of arthropods through time. Even with this evidence, however, it is difficult to link variation in total arthropod abundance to the availability of specific species of arthropods that comprise the diets of specific migrants.

Another difficulty in interpreting patterns in energetic condition is the close proximity of the vegetation types to one another. A single individual bird could readily move among these vegetation types. Thus, a birds' energetic condition might reflect the quality of the entire study area (or larger area), rather than the vegetation that it was captured in. We have some evidence that this is not a large problem. For instance, Yong and others (1998) show that, for Wilson's

Warblers in spring, 88 percent of recaptures occur in the same vegetation type where the original captured occurred; this pattern was weaker (53 percent) in the fall. Nonetheless, it is important to recognize that individuals captures in a particular vegetation type might not depend solely on that vegetation. For these same reasons, any negative effects that saltcedar may have on migrants would likely be less apparent when it is part of a mosaic of different vegetation types.

In summary, we found evidence that saltcedar contained a lower diversity of migrants, but that overall bird abundance in saltcedar was intermediate among other vegetation types. Evidence on the effects of saltcedar on mass and fat score of migrants was mixed. The mixed nature of our results is similar to those of other studies done on the effects of saltcedar on bird communities. An important consideration in interpreting these results is the configuration of the vegetation types on the landscape.

Acknowledgments

We thank the Bosque del Apache National Wildlife Refuge, particularly John Taylor and Phil Norton. M. D. Means provided masterful database management and technical support. For field work we thank S.E. Allerton, G.R. Bodner, D.L. Hawksworth, M. D. Means, B.R. Rasch and H. Walker.

References

- Anderson, B.W., Higgins, A. & Ohmart, R.D. 1977. Avian Use of Saltcedar in the lower Colorado River Valley. pp. 128-136. In Johnson, R.R and Jones, D.A. eds. Importance, preservation, and management of riparian habitat: a symposium. General Technical Report, RM-43. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 217p.
- Carothers, S.W. and Johnson, R.R. and Aitchison, S.W. 1974. Population structure and social organization of southwestern riparian birds. *American Zoologist*. 14:97-108.
- Ellis, L.M. 1995. Bird use of saltcedar and cottonwood vegetation in the Middle Rio Grande Valley of New Mexico, USA. *Journal of Arid Environments* 30:339-349.
- Farley, G.H., Ellis, L.M., Stuart, J.N. and Scott, N.J., Jr. 1994. Avian species richness in different aged stands of riparian forest along the middle Rio Grande, New Mexico. *Conservation Biology* 8:1098-1108.
- Finch, D.M. and Yong, W. *In press*. Landbird migration in riparian habitats of the middle Rio Grande. *Studies in Avian Biology*.
- Flather, C.H., Joyce, L.A. and Bloomgarden, C.A. 1994. Species endangerment patterns in the United States. General Technical Report RM-241. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 42p.
- Helms, C.W. and Drury, W.H. 1960. Winter and migratory weight and fat: field studies on some North American buntings. *Bird-Banding* 31:1-40.
- Hink, V.C. and Ohmart, R.D. 1984. Middle Rio Grande Biological Survey. report submitted to U.S. Army Corps of Engineers, Albuquerque, New Mexico. 160.
- Howe, W.H. and Knopf, F.L. 1991. On the imminent decline of Rio Grande cottonwoods in central New Mexico. *Southwestern Naturalist*. 36:218-224.
- Hunter, W.C. Anderson, B.W., and Ohmart, R.D. 1985. Summer avian community composition of tamarisk habitats in three southwestern desert riparian systems. pp128-134. In Johnson, R.R. Ziebell, C.D., Patten, D.R., Ffolliot, D.R. and Hamre, R.H., eds. *Riparian Ecosystems and their management: reconciling conflicting uses*. General Technical Report, RM-120, Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 523pp.
- Hunter, W.C., Ohmart, R.D., and Anderson, B.W. 1988. Use of exotic saltcedar (*Tamarisk chinensis*) by birds in arid riparian systems. *Condor* 90:113-123.
- James, F. C. and Rathbun, S. 1981. Rarefaction, relative abundance, and diversity of avian communities. *Auk* 98:785-800.
- Ludwig, J.A. and Reynolds, J.F. 1988. *Statistical Ecology*. John Wiley and Sons. New York.
- Reid, W.V. 1998. Biodiversity Hotspots. *Trends in Ecology and Evolution*. 13:275-280.
- Stevens, L. Brown, B.T. Simpson, J.M., and Johnson, R.R. 1977. The importance of riparian habitat to migrating birds. pp. 156-164. In Johnson, R.R and Jones, D.A. eds. *Importance, preservation, and management of riparian habitat: a symposium*. General Technical Report, RM-43. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 217p.
- International Association of Fish and Wildlife Agencies 1992. The economic contributions of bird and waterfowl recreation in the United States during 1991.
- U.S. Department of the Interior and U.S. Department of Commerce. 1997. 1996 national survey of fishing, hunting, and wildlife-associated recreation.
- Wauer, R.H. 1977. The importance of riparian habitat to migrating birds. pp. 156-164. In Johnson, R.R and Jones, D.A. eds. *Importance, preservation, and management of riparian habitat: a symposium*. General Technical Report, RM-43. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 217p.
- Williams, S.O. III. 1997. Checklist of New Mexico bird species. *New Mexico Ornithological Society Bulletin* 25:51-66.
- Yong, W. and D.M. Finch. *In press*. Populations trends of migratory landbirds along the middle Rio Grande. *Southwestern Naturalist*.
- Yong, W. and D.M. Finch 1997. Migration of the Willow Flycatcher along the middle Rio Grande. *Wilson Bull.* 109:253-268.
- Yong, W., D.M. Finch, F.R. Moore, and J.F. Kelly. 1998. Stopover Ecology and habitat use of migratory Wilson's Warblers. *Auk*. 115:829-842.

Native Montane Fishes of the Middle Rio Grande Ecosystem: Status, Threats, and Conservation

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Abstract—Between 1994 and 1997, research was conducted on three native, montane species of the Middle Rio Grande Ecosystem, in the Carson and Santa Fe national forests. The focus of study was on abiotic and biotic factors that affected status, distribution, biology and habitat of these species. Results of study suggest negative interactions with non-native species and, secondarily, habitat loss as the main factors contributing to the decline of these three native species. An inverse relationship in relative abundance between Rio Grande cutthroat trout and brown trout, extirpation of Rio Grande sucker when in sympatry with white sucker, and predation experiments documenting brown trout as efficient predators of juveniles of all three species, document both the real and potential impact of non-native species.

To sustain the Rio Grande cutthroat trout (*Oncorhynchus clarki virginalis*), and the Rio Grande sucker (*Catostomus plebeius*) and chub (*Gila pandora*) we must 1) protect stocks of native fishes with barriers to migration of non-native fishes, 2) renovate and restock streams with native fish assemblages, and 3) conduct management strategies on a watershed scale to facilitate inter-mixing of populations and subsequent gene flow, and enhance the degree of security of populations in the presence of stochastic natural disasters.

When the first Europeans arrived (ca. 1540) in what is now New Mexico, 27 native fish species were believed to be in existence in the Rio Grande basin. Of these 27 species, 13 have been extirpated in all or portions of this drainage (Sublette and others 1990). For the area known as the Middle Rio Grande Ecosystem (MRGES) Sublette and others (1990) recognize 21 native species present, whereas Rinne and Platania (1995) recognize 17 as native and Smith and Miller (1986) recognize only 16. All of these authors recognize 6 species as endemic. Human influences since this historic period have dramatically changed the palette of our native Rio Grande fish fauna. Presently, there are 43-45 species extant in the Middle Rio Grande Basin (10 native, 28 non-native) and though 10 native species still persist, their range and numbers have been much reduced (Rinne and Platania 1995).

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Although loss of native fish species has been more pronounced in the lower elevation tributaries and the Rio Grande mainstream, decrease in the ranges and abundance of native species also has occurred in upper elevation, montane areas of the MRGES. For example, Rio Grande cutthroat trout (RGCT), *Oncorhynchus clarki virginalis*, now occupies only 9 percent of its historic range in the Rio Grande basin (Stumpff and Cooper 1996). Rio Grande sucker (RGS), *Catostomus plebeius*, is listed as endangered by the state of Colorado and is declining in New Mexico in the northern portion of its range (Calamusso 1992; Langlois and others 1994). Although Rio Grande Chub (RGC), *Gila pandora*, are yet widespread and abundant in the New Mexico portion of its historic range, the species is becoming reduced in range and numbers in the Colorado portion (Zuckerman and Langlois 1990). Numerous factors have been hypothesized as causing the decline of the three native upland, Rio Grande species, the major factors being the introduction of non-native species and habitat loss.

The primary objective of this paper is to present an overview of the status, threats and conservation strategies for three native, montane species based on research funded by the MRGES program and conducted in the Carson (CNF) and Santa Fe (SFNF) national forests located in north-central New Mexico (fig. 1). The first five years of research will not be finalized until autumn 1998. More detailed and specific results of research on abiotic and biotic factors affecting the three native species, that cannot be addressed in this outlet, will be reported in the future. Accordingly, initial results of research are used to document and support recommendations.

Status

Rio Grande Cutthroat Trout

The Rio Grande cutthroat trout is one of two salmonids native to New Mexico and one of four salmonids native to Colorado (Sublette and others 1990; Alves 1998). It is a member of the inland cutthroat trouts (Behnke 1991), and is the southern most occurring of the group. While the historic range of the RGCT is not definitely known, it is likely that the species occupied all waters capable of supporting trout in the Rio Grande drainage and the headwaters of the Canadian and Pecos River drainages of New Mexico and south-central Colorado (Sublette and others 1990). Stumpff and Cooper (1996) speculate that this distribution may have covered approximately 40 hydrologic sub-basins in Colorado and New Mexico and may have extended as far

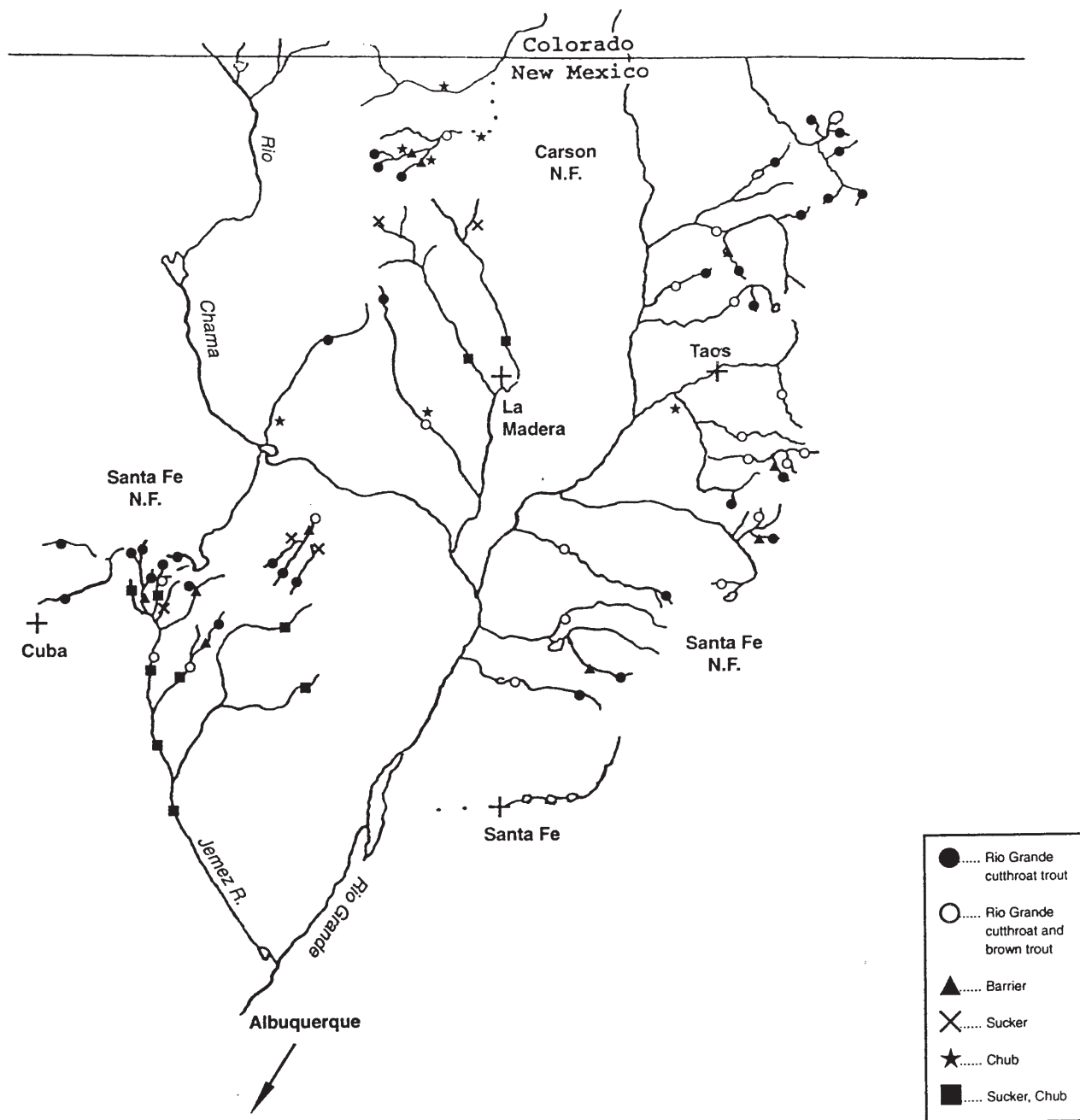


Figure 1—Study area including the current distribution of Rio Grande cutthroat trout relative to brown trout and the distribution of Rio Grande sucker and chub in the Rio Grande drainage of the Carson and Santa Fe National Forests, New Mexico as of January 20, 1998.

south as Mexico (Behnke 1992). Ninety-two populations of genetically pure RGCT exist today, 53 in New Mexico and 39 in Colorado. Most of these populations are found within United States Forest Service (USFS) lands. In New Mexico, the RGCT occupies only 9 percent of its former range (Stumpff and Cooper 1996). Most streams inhabited by RGCT are small, low productivity headwater streams where space and resources are limited. Gene flow among these disjunct and isolated populations is almost non-existent.

Currently, only 47 populations of pure RGCT remain in the Upper Rio Grande Ecosystem (URGES) and MGRES of

New Mexico (fig. 1). All are listed as “at risk/stable” by the New Mexico Department of Game and Fish (NMDGF). Nine additional populations pure and putative RGCT, representing a 19 percent increase in known populations, were identified by our surveys from 1994-1997 (table 1).

In response to the decline in RGCT stocks, the subspecies has been classified by the Colorado Division of Wildlife (CDOW) as a “species of special concern”, and by the NMDGF as diminishing— “A species that is absent from significant portions of its historic range, yet self-sustaining populations exist.” The USFS classifies the subspecies as a sensitive

Table 1—New distributions for Rio Grande cutthroat trout, CNF and SFNF, 1994-1998.

Stream	UTM	Elevation (m)
American Creek	338460E,3984710N	2,500
Canada de Osha	446050E,4002240N	2,400
Comales Creek	447750E,4001190N	2,583
Agua Piedras	452640E,3998770N	2,583
Rio de las Trampas	429450E,4001150N	2,209
Rio San Leonardo	439360E,3988900N	2,720
Rito de las Palomas	338260E, 3984350N	2,488
Italianos Creek	455620E, 4048670N	2,652
Yerba Creek	453430E,4046970N	2,497

species (Rinne and Medina 1996)—“A species that is in jeopardy of becoming threatened with extinction.” In 1989, the RGCT was listed in a federal “notice of review” as a “category C” subspecies—“taxa that are now considered to be more abundant and/or widespread than previously thought.” (Williams and others 1989). It currently is under consideration for listing as a threatened species.

Rio Grande Sucker

The Rio Grande sucker, an obligate riverine fish, was once common in the Rio Grande and its tributaries from southern Colorado to southern New Mexico (Cope and Yarrow 1875; Ellis 1914; Minckley 1980; Koster 1957, Zuckerman and Langlois 1990; Sublette and others 1990). At present, RGS are extant in the Rio Grande, primarily north of the 36th parallel and its tributaries primarily north of the 33rd parallel (Sublette and others 1990; Calamusso, unpublished data). Populations of this small mountain sucker have declined throughout the MRGES (Calamusso 1992; Calamusso and Rinne 1996) and are listed by the CDOW as endangered in the URGES of Colorado (Langlois and others 1994). After sampling over 250 streams in the early 1990's, Zuckerman and Langlois (1990) reported only two locations for RGS in the URGES. Since that time one of these populations has been extirpated and one persists (Hot Creek). Recently, the CDOW has restored two streams for RGS (Kelly 1997). The decline in RGS stocks have been attributed to the introduction and expansion of non-native white sucker, *Catostomus commersoni*, however, empirical data which identifies the competitive advantages of white sucker are needed to support this hypothesis.

Stream surveys conducted by the CNF and USFS Rocky Mountain Research Station (RMRS) (1992-1997) identified a total of 14 populations of RGS in the study area. Three streams on the CNF and eleven streams on the SFNF contain the native sucker (fig. 1). Surveys of streams which were determined to have suitable RGS habitat on the SFNF (Jemez Drainage) revealed robust populations of RGS. Streams on the SFNF draining into the Chama River were found to have populations of pure RGS or RGS in sympatry with white sucker. Only three populations of RGS were found on CNF where 5 populations once were known to exist. Many Rio Grande tributaries draining the CNF and adjacent lands exhibited habitat characteristics suitable for RGS but did not contain the species. These tributaries now are inhabited by the white sucker. In contrast to the CNF,

streams in the Jemez drainage of the SFNF do not contain white sucker due to the barrier to migrating non-native fishes from the Rio Grande mainstem created by the Jemez Canyon dam. Similar to RGCT, populations of RGS are often fragmented which limits genetic exchange among populations. Based upon the endangered status of RGS in Colorado and its decline on the CNF we consider the RGS as “imperiled” in the northern portion of its range.

Rio Grande Chub

Inhabiting both riverine and lacustrine habitats, the endemic Rio Grande chub is widely distributed throughout the MRGES and URGES. It is found in the Rio Grande and its tributaries primarily north of the 33rd parallel (Sublette and others 1990; Calamusso, unpublished data). Declines for this species have been greater in the URGES than the MRGES (Zuckerman and Langlois 1990).

RGC were found in 17 streams in the study area; 9 on the CNF and 8 on the SFNF and were found at all historic locations. Elevations in these streams ranged from 1,717 to 2,810 meters. RGC were commonly sampled in streams exhibiting habitat characteristics that are preferred by the native chub (fig. 1). In contrast to both the RGS and RGCT, gene flow among chub populations is fluid. The status of the RGC is listed as stable and reproducing for New Mexico (Sublette and others 1990; Calamusso and Rinne 1996).

Co-occurrence of Native Fishes

Co-occurrence of two or more of the native species was documented in only 10 streams within the study area (table 2). Streams exhibiting co-occurrence for all three native species was greatest in the Jemez drainage of the SFNF and lowest on the CNF. RGC and RGS were found in sympatry at lower elevations, whereas RGCT and RGS were found in sympatry at higher elevations. When RGCT were found occurring with the native cypriniforms their numbers were very low due to an abundance of non-native salmonids present in the lower elevation reaches. The low number of streams (n=3) exhibiting co-occurrence of all three of the formerly sympatric species reflects the degree of fragmentation to which the natives have been subjected.

Table 2—Co-occurrence of Rio Grande cutthroat trout, sucker and/or chub, Carson and Santa Fe National Forests, 1994.

Stream	Rio Grande cutthroat trout	Rio Grande sucker	Rio Grande chub
Carson NF			
Rio Tusas	X	X	
Canjilon Creek	X		X
El Rito	X		X
Rio San Antonio	X		X
Rio Nutrias	X		X
Santa Fe NF			
Rio de las Vacas	X	X	X
Rito de las Palomas	X	X	X
American Creek	X	X	X
Canones Creek	X	X	

Threats

Habitat degradation, dewatering and grazing have all been cited as factors contributing to the decline of many native species (Rinne and Minckley 1991). We can assume that RGCT populations are limited due to declining habitat conditions. Grazing studies, however, are limited for the Southwest and none have shown a direct link to the decline in native fishes, especially cypriniform fishes (Rinne 1988; Rinne 1998; Rinne in press). For example, in our habitat studies of RGS, two streams, the Rio Tusas and Rio de las Vacas exhibited severely grazed riparian stream reaches with a high width to depth ratio, but had the greatest relative abundance of all streams surveyed that contained RGS. Thriving populations of RGS and RGC have been reported in a reach of the Rio San Jose which receives sewage discharge from Grants, New Mexico (AquaScience 1982). Dewatering of montane streams for irrigation and acequia systems has and will continue to occur. We view these as contributing-secondary factors in the reduction in range and numbers of montane Rio Grande native fishes. Our research indicates that the principal threat to these native fishes is the expansion in range and numbers and continued introduction of non-native fishes.

Rio Grande Cutthroat Trout

Except for the westslope cutthroat trout, native to the Salmon and Clearwater drainages in Idaho and to the John Day River drainage in Oregon, interior cutthroat trout evolved apart from rainbow, *Oncorhynchus mykiss*, and redband trout, *Oncorhynchus mykiss gairdneri*. They lack innate isolating mechanisms that would allow them to coexist with those forms and with non-native trout species (Behnke 1992). Of the 86 populations of RGCT (Grade A - F) recognized in the study area 24 (28 percent) are considered to be introgressed with rainbow trout genes or some form of non-native cutthroat trout (NMDGF, Unpublished Data). Snake River cutthroat trout, *Oncorhynchus clarki* subsp. were stocked in New Mexico until the late 1980's, whereas rainbow trout continue to be stocked within the native range of RGCT. In an evaluation of historic RGCT streams in Colorado that were experiencing declines in populations, 72 percent were declining due to non-native trout, 14 percent to failed barriers (hence invasion from non-native fishes), whereas only 14 percent of the RGCT populations experiencing declines were attributed to poor habitat conditions (Alves 1998). The threat of introgression by non-native *Oncorhynchus* remains ever constant.

No less of a threat to the sustainability of RGCT are non-native brown, *Salmo trutta*, and brook trout, *Salvelinus fontinalis*. Preliminary information suggest this impact may be great. In American Creek, Rito Cafe, and the Rio de las Vacas there appears to be an inverse trend of density and/or biomass between the native cutthroat and the introduced brown trout (table 3). Of the 41 streams in the study area draining into the Rio Grande containing pure populations of RGCT only 13 (32 percent) are occupied solely by the cutthroat native, whereas 28 (68 percent) have brown trout co-occurring (usually in lower reaches) with RGCT. Of these 26 streams only 15 (54 percent) have pure populations of RGCT which are protected by barriers to non-native trout.

Table 3—Relative density (D) (n/hectare) and biomass (B) (kilogram/hectare) of Rio Grande Cutthroat trout (RGCT) and brown trout (BT) in study reaches in American Creek and Rito Cafe, Rio de las Vacas, Santa Fe National Forest, 1995.

Study section	RGCT		BT	
	D	B	D	B
American Creek				
1	324	9	279	22
2	702	32	0	0
3	90	6	90	13
4	488	13	195	9
5	300	9	486	12
6	89	5	714	58
7	56	5	617	46
Rito Cafe: Below Barrier				
1	676	14	2801	241
2	400	15	2300	182
3	0	0	3200	144
4	0	0	3875	96
Rito Cafe: Above Barrier				
5	2545	30	91	30
6	2608	36	0	0
7	1080	22	83	5
Rio de las Vacas: Below Barrier				
1	0	0	318	18
2	117	2.7	233	10
3	0	0	595	60
4	156	2.4	739	43.3
5	0	0	1468	83.7
6	61	.55	1908	118.9
Rio de las Vacas: Above Barrier				
1	3905	133.3	0	0
2	2827	153.7	0	0
3	3386	121.4	0	0
4	2548	121.0	0	0

Rio Grande Sucker

Little information exists on interactions of RGS with non-native species. Zuckerman and Langlois (1990) speculated that declines in RGS abundance in Colorado were due to genetic swamping by white sucker. They reported capturing hybrids of RGS and white sucker in two streams in southern Colorado. Recent genetic studies, however, found no evidence of hybridization of RGS with white sucker (Sue Swift, USFS, Pers. Com.) and while the mechanism of decline in RGS populations is unknown, RGS populations have been observed to decline across their range when in sympatry with the non-native white sucker.

In the 1980's five streams in the CNF were listed as containing RGS. Our surveys found only two streams inhabited solely by RGS (Rio Tusas, Little Tusas), one stream had white sucker in co-occurrence with the native (Rio Vallecitos), and in two streams the native sucker had been completely replaced by the white sucker (Rio Costilla, Rio Grande del Rancho). Presently, a beaver dam protects the Tusas system from intrusion by white sucker and while the Rio Tusas and Little Tusas appear free of white sucker, the Rio Vallecitos has white sucker established in the lower and middle reaches (up to Canon Plaza). The absence of white sucker in the

upper reaches of the Rio Vallecitos near Hopewell Lake may only be temporary as white sucker were found further upstream in 1995 than in 1992. Without a physical barrier to migration between Canon Plaza and the upper reaches, intrusion by white sucker would seem imminent. At present, all streams draining into the Rio Grande and Rio Chama from the CNF have been or are susceptible to colonization by white sucker.

Streams within the Jemez drainage (SFNF) are safe from intrusion by the white sucker due to the migrational barrier created by Jemez Canyon Dam. The potential for unintentional introduction of white sucker into this system could occur from its use by fisherman as bait. White suckers have been found in the Rio Chama and in its southern tributaries (for example Canones Creek) originating on the SFNF. These streams are currently vulnerable to invasion by white sucker.

Rio Grande Chub

Probably least studied of the three native species is the Rio Grande chub. While the RGC is considered to be common and is abundant throughout the study area a general decline in this native cyprinid has been observed in the URGES (Zuckerman and Langlois 1990). RGC are capable of exploiting both lentic and lotic habitats, this may allow the RGC to maintain its general abundance in the MRGES. Factors such as dewatering and grazing in riparian areas may have a negative effect on RGC populations since the species is commonly associated with aquatic vegetation, instream woody debris, and overhanging riparian vegetation.

Interactions of Brown Trout with Cypriniformes

As with RGCT, brown trout have been suspected in contributing to the decline in RGS and RGC populations, although no published data existed prior to this study. To test this predation hypothesis we used instream experimental cages in which brown trout, RGS, and RGC were placed together. Results from this experiment were dramatic yet perhaps inconclusive. In the instream cages, predation on the natives by brown trout was severe. Yet in light of these results if one examines electrofishing data from the Rio de las Vacas an inverse relationship between brown trout abundance and cyprinid abundance is not evident (fig. 2). It may be that brown trout do not extirpate these cyprinids, but do depress the natural abundance that would occur in the absence of the non-native predator. What the abundance of these cyprinids would be in the presence of the native cutthroat can only be speculated since there are so few instances where healthy populations of RGCT, RGS, and RGC co-occur.

In summary, our data indicates that non-native fishes are the main vector of demise for the three native species in our study area. Non-native salmonids can be directly linked to the decline of RGCT stocks in the study area and throughout its historic range. The impact of white sucker through potential genetic swamping, aggression, or greater fecundity along with predation by brown trout may act in concert

to extirpate stocks of RGS. Habitat degradation and overall environmental decline may play a role in the demise of native fishes in the montane reaches of the MRGES. Declining habitat conditions may make the natives less fit to compete with non-natives, however data is not available to support this hypothesis. At present our ability to measure and identify these mechanisms may be lacking.

Conservation and Management: Current Management

Rio Grande Cutthroat Trout

Management directed toward the sustainability of the RGCT has been ongoing since the 1970's when extensive distributional surveys were conducted by the CDOW, NMDGF and the USFS. The search for unknown populations of pure RGCT continues. Both the CDOW and the NMDGF have developed and are implementing RGCT management plans (Stumpff and Cooper 1996; Alves 1998). To insure the persistence of existing stocks of RGCT, agencies continue to build and identify sites for migrational barriers to non-native salmonids. In an effort to increase the number of RGCT populations, renovation of streams for the reintroduction of RGCT into its historic range is one of the major management practices presently being used by both states. Two brood stocks are maintained in Colorado, one in Haypress Lake and the other at the Fish Research Hatchery in Fort Collins. The NMDGF is in the process of developing a RGCT brood stock at the Seven Springs Hatchery. The RMRS continues to conduct research aimed at identifying habitat variables that influence RGCT productivity, spawning success, and recruitment and is beginning to evaluate population characteristics to develop population viability analyses that will help predict the sustainability of specific RGCT populations. Progress toward the goal of sustaining RGCT stocks, however, is slow and may be losing ground. Funding of restoration and protection programs is still a limiting factor.

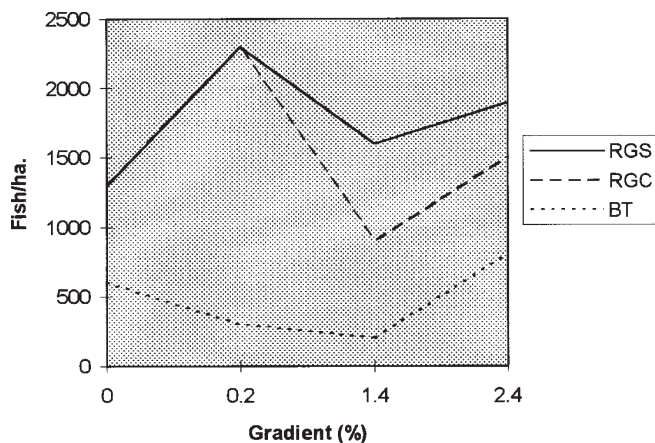


Figure 2—Relative abundance of RGS, RGC and brown trout in the Rio de Las Vacas.

Rio Grande Sucker

In response to the decline of the RGS in the URGES the CDOW initiated a Rio Grande Sucker Recovery Plan partially funded by Great Outdoors Colorado Lottery monies (Kelly 1997). Population and habitat surveys were conducted in Hot Creek, the one remaining stream that contained RGS along with examining streams in New Mexico where RGS are abundant. In 1996 the CDOW captured 200 RGS from the Rio Tusas (CNF) and released them in Medano Creek, which flows into a closed basin where access by non-native fishes is impossible. Prior to RGS being released in this drainage, the CDOW had restored this stream for RGCT. If the transplant of RGS is successful, RGC will be transplanted into this drainage to complete the native fish assemblage. In an effort to create a third population, 54 RGS were transplanted from Hot Creek to San Francisco Creek, a nearby drainage. Identification of suitable reintroduction sites in Colorado is ongoing.

Although the RGS is in general decline in the MRGES of New Mexico it is still considered common and is not afforded any special protection or status by the NMDGF. We speculate, however, that there will be a further decline in RGS in the CNF, tributaries of the Chama River (CNF, SFNF) and in any remaining unprotected drainages emptying into the Rio Grande drainage. Because of the threat of decline, the RMRS continues its efforts to identify remaining populations of RGS in the MRGES and in Rio Grande tributaries of southern New Mexico. The RMRS also has plans to develop population viability models for RGS populations in New Mexico.

Rio Grande Chub

Currently, RGC are not actively managed or afforded protection in New Mexico, however, efforts are being made in the URGES by the CDOW to restock the chub in historic waters. The CDOW continues to search for streams where the native fish assemblage (RGCT, RGS, RGC) can be reintroduced. The RMRS will continue to conduct distributional and habitat surveys to further define the role of RGC in the aquatic ecosystems of the MRGES.

Management Recommendations and Future Conservation Goals

To sustain the native montane fishes of the MRGES we believe management and research should proceed by evaluating the specific requirements of each species and their requirements in the context of the aquatic community. To that end we suggest the following for each species and the aquatic ichthyofaunal community:

Rio Grande Cutthroat Trout

To conserve the Rio Grande cutthroat trout resource, managers of all agencies must have the latest information on this cutthroat subspecies's distribution and status. Distributional and population data for this rare southwestern trout are dynamic. The addition of 7 new populations of

RGCT during the 1994 field season and the confirmation of the Rito de las Palomas and American Creek as pure in 1998 suggests that despite almost two decades of effort toward sustaining this Southwestern cutthroat subspecies, much is yet unknown about its distribution and status. Continued effort toward defining the distribution of this subspecies in New Mexico and Colorado is warranted. Of primary importance is the protection of existing pure stocks of RGCT. Placement and the maintenance of barriers to upstream migration from non-native salmonids, though reducing gene flow among populations, appears to be the only viable method in light of the wide distribution of non-native salmonids in the Southwest. Accordingly, there is an urgent and continuing need to define the extent and degree of impact of introduced salmonids, especially brown, on RGCT. Restoration of streams will be necessary to increase the number of pure populations in the subspecies' former range. Hatchery facilities need to be dedicated to the maintenance of a variety of high quality RGCT genetic strains which can be combined to replicate gene flow that is now not viable in nature due to the lack of connectivity among cutthroat populations. Stocking of non-native trout in watersheds that contain pure populations of RGCT must cease. All too often unknowing fisherman inadvertently stock non-native fishes above barriers not realizing the consequence of their actions. Research to define population dynamics (fecundity, recruitment, age class structure, longevity) is needed to begin to develop population viability analyses to determine the potential long term persistence of pure populations of RGCT.

Rio Grande Sucker

Surveys to identify unknown populations of RGS need to continue. Similar to RGCT, known populations of RGS warrant protection from invasion by the white sucker and non-native salmonids. Instream barriers need to be constructed for tributaries draining to the Rio Grande and Chama River.

While streams within the Jemez drainage are currently safe from intrusion by the white sucker due to Jemez Canyon Dam white sucker may eventually be introduced into this system via bait bucket. Regulations may be warranted to limit any use of non-native bait or to prohibit the use of bait in the Jemez system above the Jemez Canyon Dam. White sucker have been found in the Rio Chama and in its southern tributaries (for example Canones Creek). Here, the only way to prevent white sucker from expanding its range into streams containing RGS would be the placement of barriers. Due to the precarious status of northern populations of RGS protection of populations of RGS in isolated Rio Grande tributaries in southern New Mexico should be considered. Restoration efforts should identify those waters having modest gradients (<2.5 percent) with well developed glide/pool habitat within a mosaic of various habitat types.

Rio Grande Chub

Continued delineation of the distribution of the RGC throughout the MRGES and its entire range is warranted. Monitoring of RGC populations is also necessary to ensure long-term sustainability.

Further, the recommendations suggested for the individual species should be incorporated on a watershed scale. Management or stream renovation of isolated reaches will not be enough to sustain the native fishes of the MRGES. Managing on a watershed scale incorporates a greater diversity of aquatic habitats, thereby increasing ichthyofaunal diversity. Gene flow among various stocks of native fishes is enhanced and the effects of stochastic events is dampened. The Rio de las Vacas (SFNF) of the Jemez River drainage is a watershed that has the potential to be managed on this large landscape approach. Currently, all three native species, along with the native longnose dace, *Rhinichthys cataractae*, occur and are abundant in this drainage. At the lower reaches of the Jemez River the system is protected from intrusion from non-native fishes from the Rio Grande by Jemez Canyon dam. A migrational barrier would have to be constructed at the lower reaches of the Rio de las Vacas and subsequent stream renovations would be needed to remove non-native fishes, primarily brown and rainbow trout. The monetary and logistical costs of this project would be substantial, however the benefits to the sustainability of native fishes would be great.

Conclusions

To sustain native fishes of the MRGES protection of its aquatic habitats and the resultant aquatic community should be the primary goal of any management plan. Future management must address the threats from non-native species identified by this research. Restoring native species to their former range and managing aquatic communities on a watershed scale will address the losses realized over decades of misguided fish introductions and habitat degradation. With additional funding and management plans incorporating these two approaches future persistence of native fishes may be assured.

References

- Alves, J. 1998. Status of Rio Grande Cutthroat trout in Colorado. Unpublished Report of the Colorado Division of Wildlife. 10 pp.
- AquaScience, Inc. 1982. Suitability of Rio San Jose water for fish. Report No. 301-312, March 1982.
- Behnke, R. J. 1992. Native trout of western North America. Amer. Fish Soc. Monograph 6: 1-275.
- Calamusso, B. 1992. Current distribution of *Catostomus plebeius* and *Gila pandora* on the Carson National Forest, New Mexico with preliminary comment on habitat preferences. Proc. Desert Fishes Council 24:63-64.
- Calamusso, B. and J. N. Rinne. 1996. Distribution of the Rio Grande cutthroat trout and its co-occurrence with the Rio Grande sucker and Rio Grande chub on the Carson and Santa Fe national forests. pp. 157-167 In: Shaw, D. W. and D. M. Finch, (tech coords.), Desired future conditions for Southwestern riparian ecosystems: Bringing interests and concerns together. 1995 Sept. 18-22, 1995; Albuquerque, NM. Gen. Tech. Rept. RM-GTR-272.
- Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 359 pp.
- Cope, E. D. and H. C. Yarrow. 1875. Report upon the collections of fishes made in portions of Nevada, Utah, California, Colorado, New Mexico, and Arizona during the years 1871-1874. Chapter 6. pp. 635-703 In: United States Army Engineers Dept. Report, in charge of George M. Wheeler Geog. and Geol. of the Expl. and Surveys west of 100th meridian, 5, 1-1021.
- Ellis, M. M. 1914. Fishes of Colorado. Univer. Colorado Studies, 11(1): 5-135.
- Kelly, Brighed. 1997. Colorado Outdoors. Sucker Saving. Jan/Feb 1997. pp. 10-14.
- Koster, W. J. 1957. Guide to the fishes of New Mexico. Univ. of New Mexico Press, Albuquerque.
- Langlois, D., Alves, J., and J. Apker. 1994. Rio Grande sucker recovery plan. Colorado Div. Wildl., Denver. 22 pp.
- Minckley, W. L. 1980. *Catostomus plebeius* Baird and Girard, Rio Grande sucker, p. 387. In: Lee and others (Eds.), Atlas of North American Freshwater Fishes. North Carolina State Mus. Nat. Hist., Raleigh.
- Rinne, J. N. 1988. Grazing effects on stream habitat and fishes: Research design considerations. N. Amer. J. Fish Manage. 8:240-247.
- Rinne, J. N. 1998. Grazing and fishes in the Southwest: Confounding factors for research. In: AWRA/SRM Specialty Conference on Rangeland and Water Resources. May 26-30, Reno, Nevada.
- Rinne, J. N. In press. Fish and Grazing Relationships: Southwestern United States. In, Jamison R., Raish, C, and D. Finch (eds) Ecological and Socioeconomic Aspects of Livestock management in the Southwest.
- Rinne, J. N. and A. L. Medina. 1996. Implications of multiple use management strategies on native southwestern (USA) fishes, pp. 111-124. In: Meyer, R. M., C. Zhang, M. L. Windson, B. J. McCay, L. J. Husha, and R. M. Muth (editors). Fisheries resource utilization and policy. Proc. of the World Fish. Congress, Theme 2. Oxford & IBH Publ. Co., New Delhi, India.
- Rinne, J. N. and W. L. Minckley. 1991. Native fishes of arid lands: A dwindling resource of the desert Southwest.
- Rinne, J.N. and S.L. Platania. 1995. Fish Fauna, pp. 165-175. In: Finch, D. M. and J.A. Tainter (tech eds.) 1995. Ecology, diversity, and sustainability of the Middle Rio Grande Basin. Gen. Tech. Rep. RM-GTR-268. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 186 p.
- Rinne, J. N. and W. L. Minckley. 1991. Native fishes of arid lands: A dwindling resource of the desert Southwest.
- Rinne, J.N. and S.L. Platania. 1995. Fish Fauna, pp. 165-175. In: Finch, D. M. and J.A. Tainter (tech eds.) 1995. Ecology, diversity, and sustainability of the Middle Rio Grande Basin. Gen. Tech. Rep. RM-GTR-268. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 186 p.
- Stumpff, W. K. and J. Cooper. 1996. Rio Grande Cutthroat trout, *Oncorhynchus clarki virginalis*. in D.E. Duff (editor), Conservation Assessment for Inland Cutthroat Trout. USDA Forest Service, Intermountain Region, Ogden, Utah.
- Sublette, J. E., M. D. Hatch, and M. Sublette. 1990. The fishes of New Mexico. Univ. of New Mexico Press, Albuquerque.
- Williams, J.E., J.E. Johnson, D.A. Hendrickson, S. Contreras-Balderas, J.D. Williams, M. Navarro-Mendoza, D. E. Mcallister and J.E. Deacon. 1989. Fishes of North America endangered, threatened, or of special concern: 1989. Fisheries 14(6):2-20.
- Zuckerman, L. D. and D. Langlois. 1990. Status of Rio Grande sucker and chub in Colorado. Unpublished report, Colorado Div. Wildl., Montrose, CO. 44 pp.

Workshop Summary



Future of the Middle Rio Grande

Barbara A. Coe

Abstract—Because decisions made today about the Middle Rio Grande will influence future conditions, symposium participants—the stakeholders—collaborated in a final session to plan improvements for the watershed and river corridor. The result included several action plans focusing on desired future conditions and actions to achieve them.

How can a sustainable future for the Middle Rio Grande Basin be achieved? What exists now that you would like to preserve? What would you like to restore? What would you like to get rid of or change? These are some of the questions addressed by participants in the Workshop portion of the Middle Rio Grande Ecosystems Symposium. Decisions made in the past by many stakeholders have produced the current state, those things that are perceived as good or bad. Likewise, decisions made now by many stakeholders will influence the future state. Although individuals alone cannot control everything that happens, working collaboratively toward common goals can help symposium participants move much more effectively in the desired direction.

The final item on the agenda for the Symposium was a process to help participants think about and plan how to enhance the future of the Middle Rio Grande Basin. This was intended as input to the Bosque Management Plan and also to stimulate collaborative actions by participants, with this session as a start at organizing those actions. The workshop had three main purposes — to identify the desired future of the Basin, to plan some joint actions toward improvement of the Rio Grande watershed and river corridor, and to introduce an innovative and powerful way to work together to achieve goals — that can be applied to any situation.

Workshop Approach: The Path of Least Resistance

The specific process used as a framework is one designed to use the “Path of Least Resistance” to help groups successfully achieve the goals they set. Sometimes plans get implemented; sometimes they don’t. Many groups (and individuals) who use this process report that it makes a major difference in their capacity to achieve their goals.

In: Finch, Deborah M.; Whitney, Jeffrey C.; Kelly, Jeffrey F.; Loftin, Samuel R. 1999. Rio Grande ecosystems: linking land, water, and people. Toward a sustainable future for the Middle Rio Grande Basin. 1998 June 2-5; Albuquerque, NM. Proc. RMRS-P-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

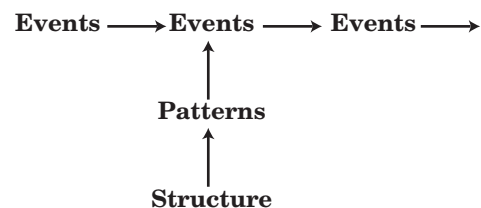
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The intended outcomes of the workshop were:

- Improved understanding of one’s own and others’ desires for the future of the Middle Rio Grande Basin.
- Improved understanding of the current state of the Middle Rio Grande Basin.
- Preliminary action plans for elements of the desired future.
- Introduction to an innovative but tested way to achieve goals collaboratively.

The approach used is drawn from discoveries about the elements of successful implementation or “the creative process” by Robert Fritz, author of *The Path of Least Resistance* (1989), *Corporate Tides* (1996), and other books and the elements of successful collaboration by Barbara A. Coe, author of articles in *the Journal of the Community Development Society* and others. It was based on extensive “grounded theory” research — discovering the principles through observation of many cases. Fritz discovered that a foundational structure underlies and determines action, not only in physical systems, but also action by individuals, organizations, and groups. For example, the motion of the water in the Rio Grande is guided by such elements as the path, depth, and slope of the riverbed, obstructions such as boulders, and barriers such as levies. The water moves along the “path of least resistance.”

So too, individuals, organizations and groups are guided by their structures along this path of least resistance. In the case of organizations and multi-organizational groups or communities such as this one, the elements of the path, or structure, include such things as individual or organizational goals, relative power relationships, information, organizational reporting relationships, or all sorts of other things. With individuals, the elements of the structure include cognitive elements such as beliefs and assumptions, along with the actual circumstances. It is necessary to look at the specific action to know what elements are guiding it. However, once the structure is identified, actions can often be predicted. Sometimes the path of least resistance leads to successful implementation, sometimes not.



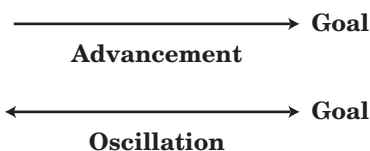
Oscillating or Advancing Patterns of Action

Two structures are common: One structure leads to a pattern of success, advancing steadily toward the goals. The other leads to a pattern of oscillation, moving toward the goals, then away, then toward again, sometimes over a long,

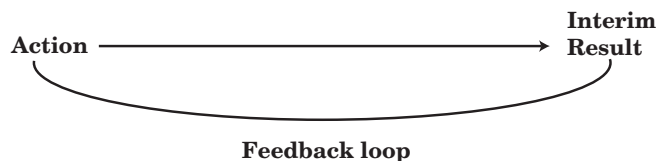
sometimes over a short, period of time. The reason for advancement is that when the desired future state and the current state are in disequilibrium, energy tends to be generated between them, so that people tend to be motivated to move toward the goals. When desires for the future are set against a clear view of the current state, this produces a sort of dynamic tension or “structural tension.” (Fritz, 1989). This tension energizes groups and helps them take and sustain the action necessary to achieve their goals. To maintain this energy requires staying clear about the current state on an ongoing basis, as it changes, as well as staying focused on the goal. Although conditions or events may sometimes preclude achievement of certain goals, the chances of success are greatly enhanced if the pattern is one of continued advancement.

When in a structure designed to lead to oscillation, however, groups take action, such as creating a plan, and then later find themselves in the same place again, perhaps creating another plan because the first one was not implemented. The reason for oscillation is that the structure has inherent contradictions among its elements, so that action cannot be focused consistently toward the goal. As Fritz says, “it is a design problem.” A structure can, however, be designed and created that leads toward the goal.

An accurate assessment of the current situation is an essential ingredient of a structure designed for successful goal implementation, but the view of the current situation is often distorted. Sometimes blanks are filled in when the information is unknown; other times assumptions are made about reality or about the future; or beliefs about how the world works distort reality. Different people tend to see things differently — this is known from many situations — for example, different people witnessing an accident will describe that accident in very different ways. Distortions of the current situation tend to contribute to oscillation. To see the current state clearly, groups must identify what is factual about the current situation, relative to the desired condition. Assumptions, beliefs, and conjectures are set aside for the purpose of creating the desired outcome.



Having the goals and the current state clearly in mind allows for flexibility of actions. Often what will lead to the desired future cannot be predicted at the outset. In the case of sustainable basins, the information is not necessarily available at the beginning. Experimentation with different approaches may be needed before reaching the goal.



When the interim result is observed and evaluated, actions may then be adjusted accordingly and then the new actions monitored and evaluated to learn if they lead toward the goals or are more efficient. This is the approach advocated in Adaptive Management.

When results, either interim results or the desired future, have been achieved, groups find that when they acknowledge this completion and actually celebrate it in some meaningful way, their energy for the next step or the next project is considerably enhanced.

The process used in the workshop was designed to produce a structure leading to advancement toward the goals for the Rio Grande; one in which the path of least resistance leads naturally toward plan implementation. The four primary elements of such a structure are:

1. A clear picture of the desired future state
2. An accurate description of the current state
3. Experimental actions (or adaptive management)
4. Completion and celebration

In a situation requiring the participation of different agencies and stakeholders, a structure designed to advance also tends to include the elements of linking communication, collaborative vision, and evocative leadership (1988, 1990, and 1998).

The Process

The group gathered at about 10:30 p.m. for the workshop to begin the work of producing a preliminary plan for the future of the Middle Rio Grande Basin. Groundrules for working together were suggested and agreed-upon by the group:

- Listen to learn and understand
- Share the spotlight
- Talk one at a time
- Respect all ideas

1. Looking for Common Ground. In this process, participants looked for their “common ground” — what they shared — regarding their desired future of the Rio Grande Ecosystems. Participants formed into five small groups (organized based on the animal logos on their folders) and began to address their Desired Future Condition or Future State of the Middle Rio Grande Basin.

They first selected a timekeeper, recorder, reporter, then introduced themselves briefly, indicating their name, a major activity related to the Rio Grande and a one word descriptor of something they appreciate about the Middle Rio Grande Basin.

They then brainstormed about the elements of the desired future state, making sure everyone had a chance to speak, and using the flipcharts to make the notes so as to help everyone focus on the same thing at the same time and make it easier to process the ideas.

The next step was to get clarification about the items when necessary, and then to find “common ground” on five to seven elements of the desired future upon which they agreed and to write each on a half sheet of paper. They were cautioned that they might identify some items upon which they didn’t agree — but to ignore those or to put them on aside on a disagree list.

They followed these guidelines for identifying Desired Future Conditions:

- End result, not a means**
- Specific enough to know it when it is achieved, not vague**

What you want, not a problem to solve or something you don't want

Example: the Rio Grande River Basin is _____
or the Rio Grande River Basin has _____

The groups then reported out their desired future conditions as follows: One of the groups was asked to name one element of their desired future conditions. Their half sheet was placed on the wall. Other groups with that same element were asked to place theirs with the first one. The next group was asked for the name of one of their elements and the process was repeated until the names of all elements were on the wall. The elements were consolidated into six major elements which became the topics for the afternoon work.

2. Clearly Identify the Current State. The second step was to examine the current status of the Rio Grande Ecosystems, so as to be able to determine what the appropriate actions would be. Given a clear picture of the baseline, groups can devise appropriate action steps. Otherwise, actions may be taken that are unnecessary, unwise, or ineffective. Furthermore, a clear and objective view of the current conditions is a necessary aspect of successful implementation, setting up and using the disequilibrium and “structural tension” between the desired and current conditions to motivate action.

To address the second step the groups were asked to “vote with their feet,” to move to that element on which they would like to do further work. The next step was to describe the Current Conditions or state, that is:

What is already in place vis a vis the desired future state — what is the baseline or current state —

- not how it got that way or
- what is next, just what is

3. Experiment with Actions and Adjust. The last part of this process was to think of some actions to try — to experiment with. Often action steps are set in concrete, but another key to successfully creating the goals is to be flexible in regard to means — similar to Adaptive Management. Some actions are taken, then evaluated to see if they get closer to the goal. If not, other actions are tried.

Groups were asked to think of at least 3 or 4 steps that they considered would lead in the direction of the desired future state. Also, they were asked, if time allowed, to write on the chart who would need to do the action and by when. They organized the results of their work into “structural tension charts” to illustrate how to get from the current state to the future state and how it sets up the energy state. Several participants indicated the need to take action and observe the results, adjusting as necessary as more information is available.

4. Complete and Celebrate. An important part of creating the desired results is to acknowledge the completion, whether of an interim step or subgoal, or of a final goal. To complete the process, each of the groups reported out its results to the other groups and asked for feedback and questions. They discussed next steps followed by concluding remarks by Jeff Whitney.

Report Out. Each group then reported on the elements of their structural tension chart as follows:

Action Plans for Achieving a Sustainable Middle Rio Grande Basin

Desired Future Condition: Sustainable local economy and agriculture and the environment and economy in dynamic equilibrium.

Actions:

- Personal choice as consumers
- Develop regulations that constrain growth based on available water supply (determine water available for development)
- Have more regulation on water use (i.e. watering lawns and washing cars with potable water)
- Promote new economic paradigms (i.e. natural capitalism); destruction of environment is economically detrimental; market regulation
- Internalize environmental costs
- Shift subsidies to environmental benefits
- Need measures of economic goods and bads in terms of ecology
- Farm days (public education)
- Reaching out to children

Current Conditions:

An artificial dichotomy between economic and ecological health
Inadequate incentives for agricultural producers to protect environment
Development that disregards the local environmental conditions (i.e. water/arid climate)
Current demands on water exceed supply
Inefficient/wasteful uses of water
Economy not constrained by the supply of water
Agriculture is given little value; no incentive to keep water on the farm
Ecological values of agriculture and nature are not recognized
Urban development is seen as economically more beneficial than other uses of resources
Perceived economic value of using future capital today
Consuming too much
Ecological services (solar energy, etc.) highly undervalued

Desired Future Condition:

Enough water of sufficient quality to sustain human culture and natural processes; a sustainable water supply; good water quality; and water conservation

Actions:

- Increase hazardous waste recycling opportunities
- Extend water conservation — municipalities now
- NPO's intensify and implement regional planning efforts — MRGCOG and local, state and federal governments, acequias, tribes, conservancy districts — via media and schools — now
- Reduce/minimize water consumption and demand — everyone, now

- Increase wetland development — public agencies, private landowners — now
- Implement NPDES non-pointsource program — EPA and NWED — now
- Manage public lands for sustainable water supply — public agencies, public water — now/5 years
- Economic incentives for turf/agricultural irrigation efficiency — State Engineer's Office/legislature and governor — next legislative session
- Increase cost of municipal and industrial water — adjust rate structure — public water suppliers — phased in now
- Re-engineer Conservancy's drainage system — Conservancy District/BOR — now

Current Conditions:

Too little processing
 Too much sediment
 Dependent on ground water — urban uses
 Inefficient irrigation systems
 Poor upland water retention
 Large areas of irrigated turf
 Urban run-off into Rio Grande
 People think they live in Ohio not the Desert Southwest
 Water Use Excessive: irrigation/sprinklers

- Flood irrigation leads to high water
- Urbanization moves water off rather than retains
- recycling/reuse minimal!

 Attitudes/public awareness changing
 City water conservation effort
 Agriculture improvements
 Intel et al., recycle/reuse
 Improving technology and ongoing research
 Planning and public Education initiatives

- Regional planning
- Evaluation

Desired Future Condition

An ecologically aware and informed citizenry: public thinks like a watershed; people connected to the river

Actions:

- Getting the public out to the river with people who know about it
 - (school kids, media, elected officials) — RGNC, ABQ Open Space, Rio Grande
- Restoration, MRGCD, FWS, NM G&F, NM Forestry, Tribes — ongoing
 - special events
 - restoration projects
 - river institute
 - mentor programs
- Take River to people: take knowledgeable people to public forums, outreach programs
 - creative advertisement
 - continuing education class, UNM
 - Elder Hostel — consortium of experts, TAG Team — by year 2000

- Media/elected officials outreach — Alliance for Rio Grande Heritage — Conservation Lobbyists — ongoing
- Foster New Partnerships among existing education and conservation programs, including tribal— Non-government activists/interested parties, local level, grass roots — 2000?

Current Conditions:

Disconnected from the river

- can't see/experience river
- Insular/out of context from the whole

 Urban people don't feel an emotional attachment to the river
 People don't understand there's a problem with the river
 Ignorance about watershed — "water comes from the tap"
 Take river for granted
 Seeds of interest/growing awareness and fears routed in misconception
 Overwhelmed/immobilized
 Confusion due to hype (El Niño)
 Grass roots activity

Desired Future Condition:

Bosque composed of diverse native vegetation: native, self-sustaining biological communities; healthy native wildlife population and habitat; salt-cedar free by 2003!

Actions:

- Increase restoration efforts
- Coordinated effort on river dynamics to enhance establishment of native vegetation — reach by reach over next 20 years, based on 20 year half life for existing cottonwood forest
 - Hydrograph
 - Sediment
 - Physical barriers — channel characteristics
- Exotics removal/impact reduction
 - Salt cedar
 - Russian olive
 - Pheasants, oryx
 - Cattle
 - Fishes
- Protect what we've got
- Effective for management to maintain native biota
 - Corridors
 - Control over known detrimental interspecies relationships
 - Application of existing knowledge
 - Targeted habitat restoration for specific SPP.
- Monitor wildlife/habitat response to restoration efforts

Current Conditions:

Exotics replacing natives
 Lack of effective native species reproduction
 Declining wildlife and habitat
 Monocultures
 Lack of a diverse mosaic of habitats
 Limited/underfunding of wildlife-habitat relationships

Desired Future Condition:

Collaborative Efforts: good people interaction to create win-win solutions; legal framework for sustainable uses (i.e. urban planning, water conservation, water adjudication, preservation of agricultural lands; governance that is innovative and inclusive of people

Actions:

- Train community mediators
- Conduct institutional analysis
- Create collaboration plan — for agencies
- Break down institutional boxes
- Demo projects: win-win solutions are possible
- Test pilot projects to hold management accountable
- Citizen review board: Referendum #9
- Hold management accountable to implement collaborative process: clean house
- Fund agencies to implement collaborative processes
- Reform institutional missions toward collaborative processes
- Train people to be responsible citizens: of services to communities; mediation skills, etc.
- NEPA CEQ: rewrite implementing regs go through fear and danger

Current Conditions:

Command control paradigm
One lawsuit after another
Competition for resources
Wasteful use of resources
Legal framework weighted toward consumptive uses of resources
Decisions made by elites
Water flows uphill to \$
General public feels powerless and apathetic and uninformed
Other interests unwilling to acknowledge validity of other points of view
No meaningful process in place to get diverse interests together to understand other points of view
Lack of legislative involvement
Action happens only in crisis mode

Desired Future Condition:

A functional river/riparian ecosystem capable of supporting a mosaic of habitats with viable and diverse native species; restore function potential; a reconnected river and bosque; river and watershed are healthy; functioning river systems including uplands to Rio Grande corridor; minimal physical and institutional constraints on river dynamics

Actions:

- coordinate agency management basinwide — 3 years (2001)

- Floodplain management for a sustainable Bosque — as soon as possible
 - Exotic species control
 - little removal/fire suppression
 - selective habitat restoration
- Select sites for mechanical restoration
 - remove bank vegetation
 - rework banks by channel
 - provide flows
- Augment hydrograph to ensure periodic overbank flooding — within 10 years (2008)
 - peak flows
 - timing and duration
- Monitoring — immediately

Current Conditions:

Complex infrastructure
Controlled hydrograph
Narrowing and structural constraints
Stable channel
Lack of sediment supply
Less water
Narrow floodplain
Large stands of non-native vegetation
Stands of mixed native-non-native vegetation
Disconnected River & Bosque floodplain
High fire frequency
Reduced native fish species
Lack of mosaic of successional stages
High consumer demands on water
Fragmented water allocations/drainage

Wrap up

In the wrap-up, participants expressed concern that the word “river” was heard much more than “basin.” The statement was made that ninety-five percent of the attention is being placed on five percent of the land mass because the river is a charismatic resource that captures attention. People have lost sight of where the water comes from and need to regain that awareness. People could substitute the word food for river, as well: urban people are disconnected with the source of their food. As with water, the need to reconnect with the land and the food supply is apparent.

The group also discussed the urgency of restoration of the Bosque. Of particular concern is the possibility of a very large, devastating flood, as some cities have experienced because of lack of riparian area. At the same time, the group expressed concern that actions taken with too little knowledge, especially concerning the long-term consequences of actions, may have detrimental effects. They agreed about the need to be opportunistic, to take advantage of the knowledge available, and to be flexible about how improvement is achieved.



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