GRASSLAND REHABILITATION AFTER COAL AND MINERAL EXTRACTION IN THE WESTERN UNITED STATES AND CANADA

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Introduction

Grassland rehabilitation in North America has been the subject of many publications over the past 70 years, especially since the late 1960s. The valuable information in these publications has added much to the understanding of ecosystem structure and dynamics, and many advances have been made in improving the speed and comprehensiveness of grassland rehabilitation. Yet many problems linger in returning disturbed lands to long-term biological productivity and to aesthetically pleasing landscapes.

At the beginning of the 19th century, North American grasslands were occupied almost exclusively by North American Indians. Following colonization by the European settlers, most of these grasslands were converted to agricultural use, and some were disturbed during the recovery of coal and minerals. Mining continued to expand with the increase in population, and with demands for energy and resources. No rehabilitation procedures of any significance were in place until the early 1970s, and nearly all mined lands were left in a disrupted, unvegetated state. Then in the 1960s and 1970s, environmental concerns became stronger, and reclamation practices like regrading and replacing topsoil were implemented. Many of the earlier problems were largely eliminated, but new problems crept in. We draw comparisons between the two situations, especially in regard to succession and rates of development. Finally, recommendations are given for future research needs in enhancing the rehabilitation of grassland ecosystems.

Characteristics of North American Grasslands

Geography, extent, types, and use

Roughly 15 percent of North America was covered with grasslands prior to European colonization of the continent (Risser *et al.* 1981). As with most grasslands of the world, the grasslands of North America are found primarily on plains in the interior of the continent (Fig. 1). The climate is characterized by extremes; temperatures in North American grasslands can range from -25 C in the northern extremes to 35 C in the south. Precipitation patterns characteristically involve a wet season followed by a dry season, with the total precipitation ranging from 250 mm or less annually in the shortgrass region to over 1000 mm in the eastern tallgrass region. Importantly, the distribution of precipitation is erratic.

About the year 1800, the Central Plains were characterized by huge expanses of grasslands, stretching 1600 km east to west and 4200 km north to south (Fig. 1). In general, rainshadow patterns from the Rocky Mountains coincide remarkably well

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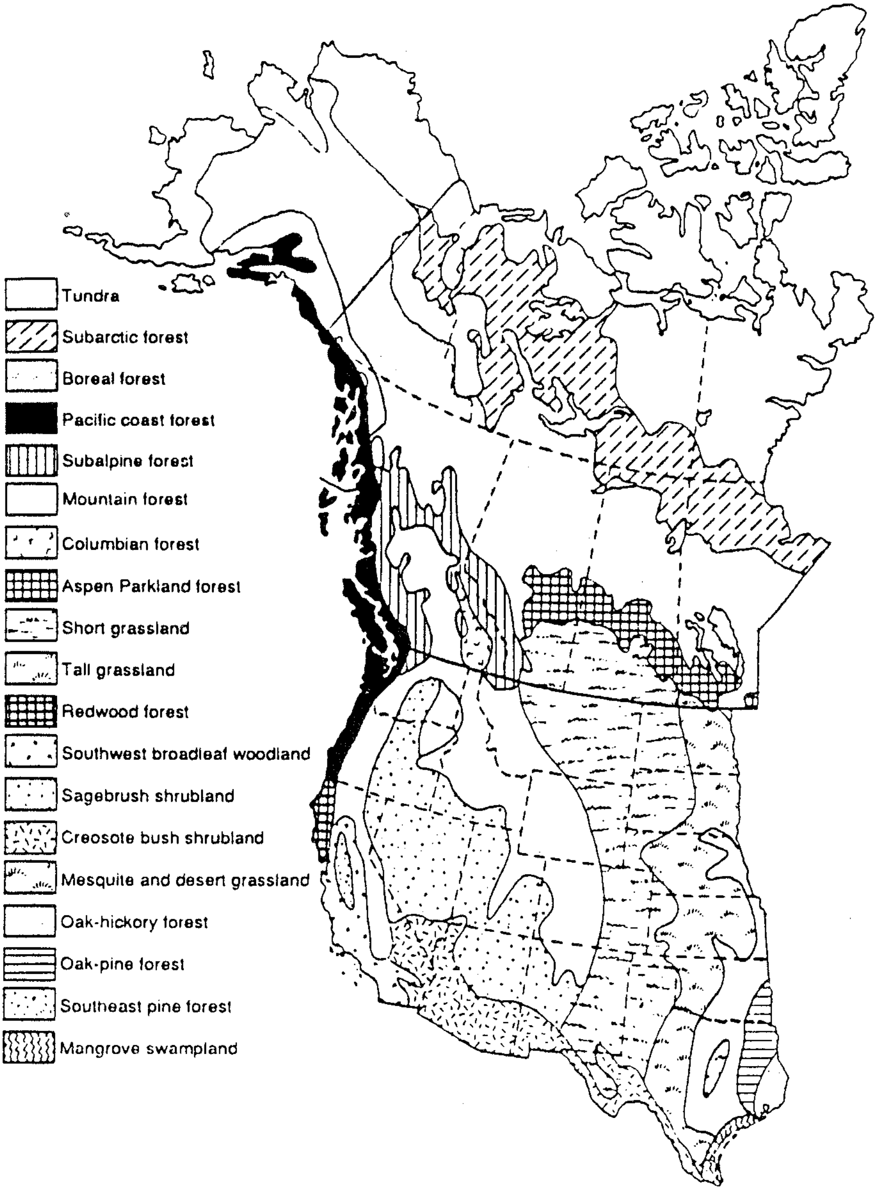

Fig. 1. Vegetation of western North America (adapted from various sources).

with the distribution of the grassland system (Borchert 1950). Precipitation decreases from east to west and so does the stature of the grass species (Sprague 1974). At least seven types of grasslands are recognized in North America: annual, desert, and mountain grasslands; shrub steppe; and shortgrass, mixed-grass, and tallgrass prairies (Kuchler 1964, Risser *et al.* 1981); a brief description of each is given below. Of these, the most important ones, occupying the mid-section of the continent and

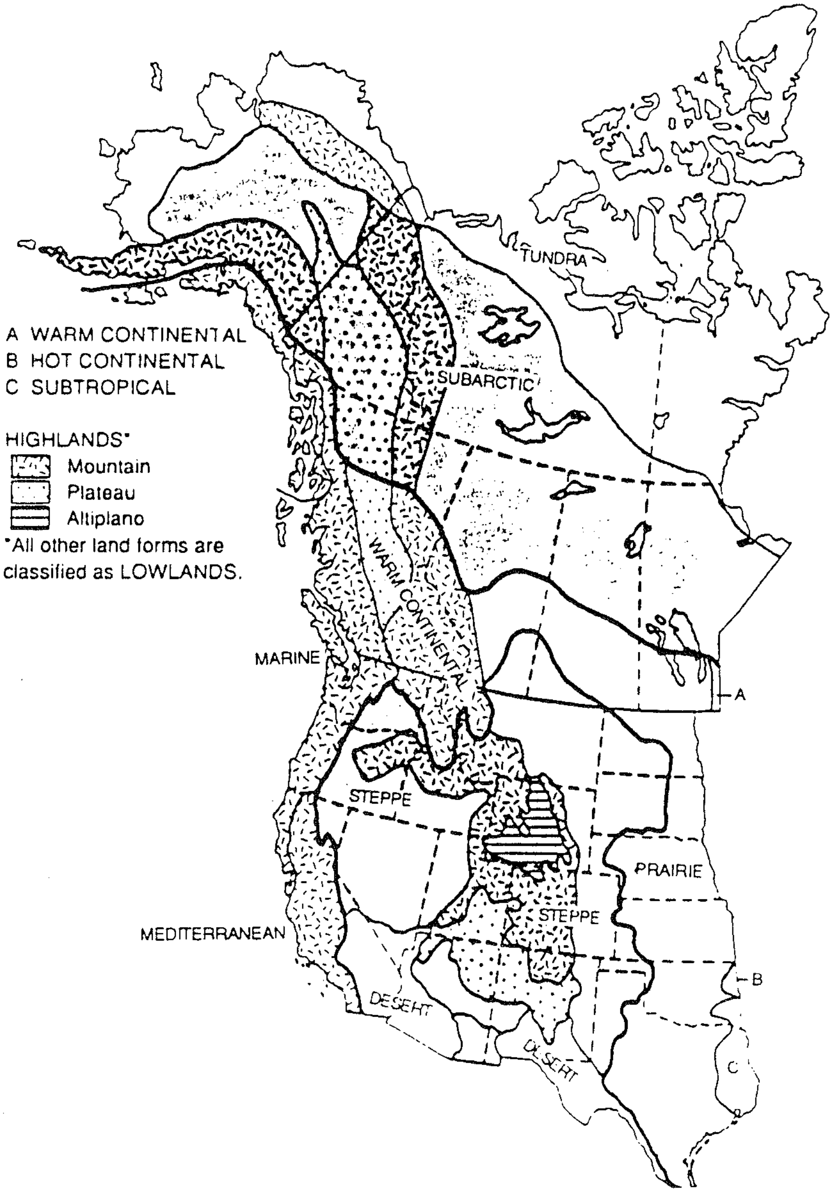

Fig. 2. Ecosystem divisions of western North America (source: Bailey 1976).

constituting 'typical' grasslands discussed in this paper, are the short-, mixed-, and tallgrass prairies.

We have included here maps showing major ecosystems (Fig. 2), physiographic regions (Fig. 3), bedrock and surface geology (Figs. 4-5), soil orders and suborders (Fig. 6), and major coal regions (Fig. 7) for the area. It must be quickly pointed out that these figures are included for the convenience of readers but it is only the site-

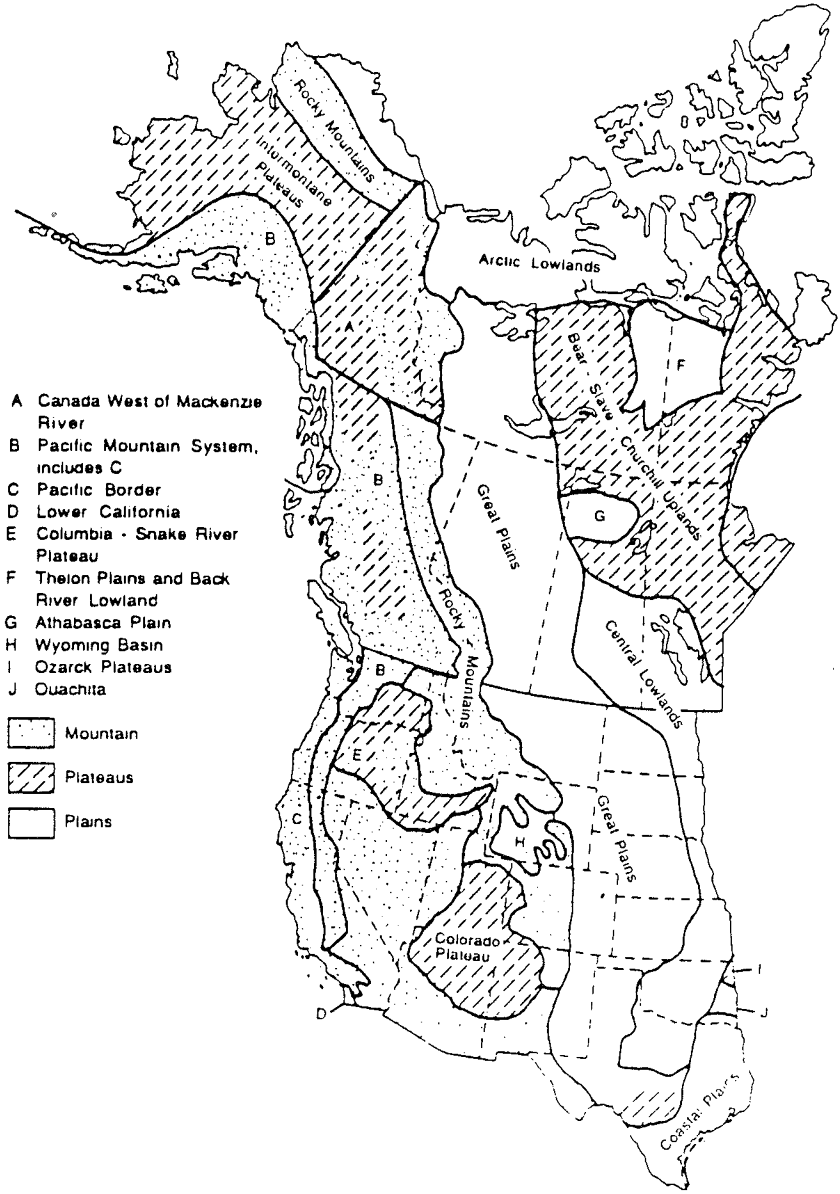

Fig. 3. Physiographic regions of western North America (source: Hunt 1974).

specific environmental conditions that govern the success of rehabilitation (Wali and Freeman 1973).

Annual grassland. This grassland type occupies approximately 52,700 km^2 of North America. It is found primarily in California and has a Mediterranean-type climate with winter rains and very dry summers; plant growth occurs primarily in the early spring. Prior to European settlement, the native vegetation was perennial bunch-

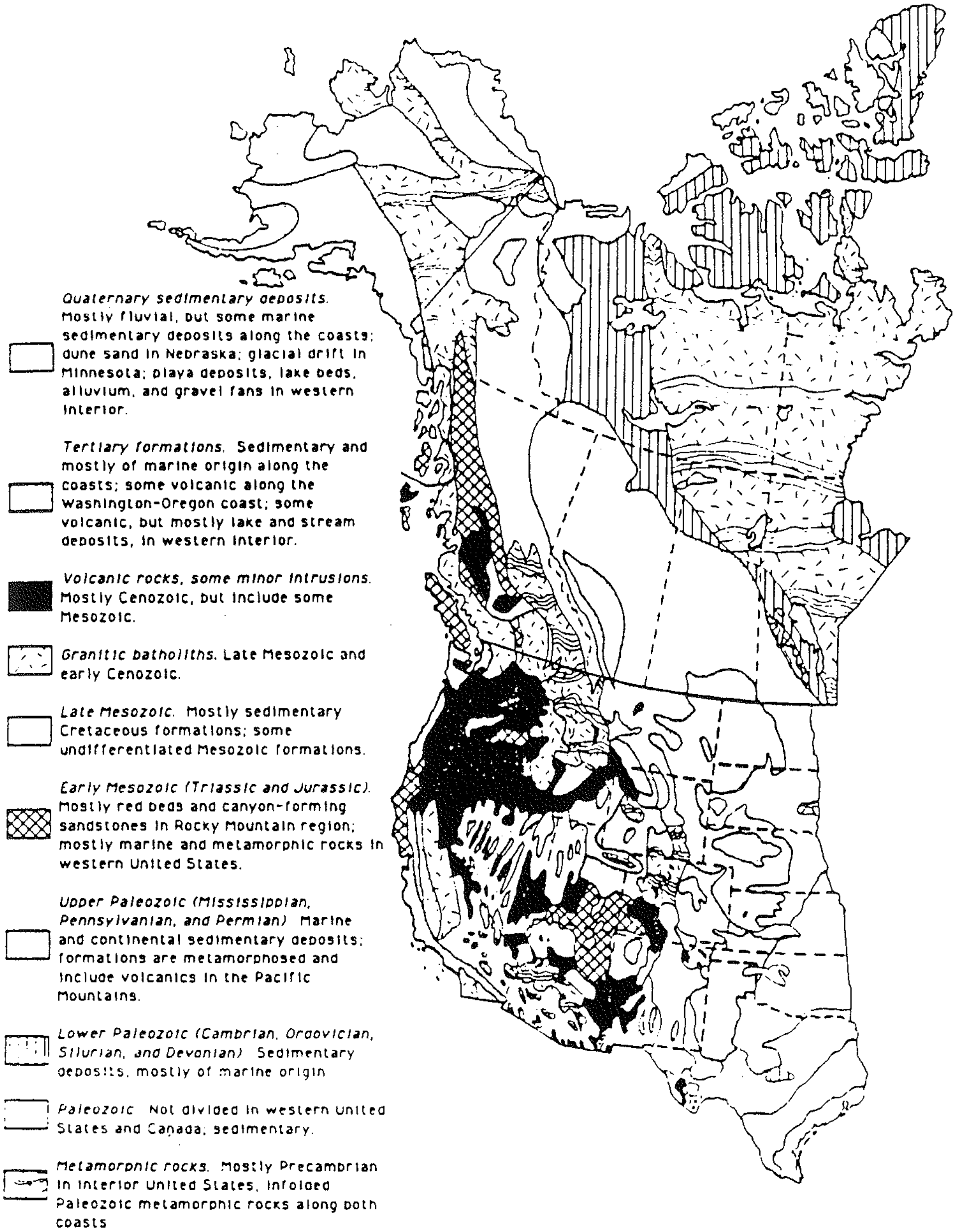

Fig. 4. Bedrock geology of western North America (source: Canada Department of Mines and Technical Surveys, 1957, Hunt 1974).

grasses dominated by members of *Elymus*, *Muhlenbergia*, *Poa*, and *Stipa*. These grasses have now been replaced by annual grasses, especially from the genera *Avena*, *Bromus*, and *Hordeum*.

Desert grasslands. This type occupies roughly 207,600 km^2 in the southwestern

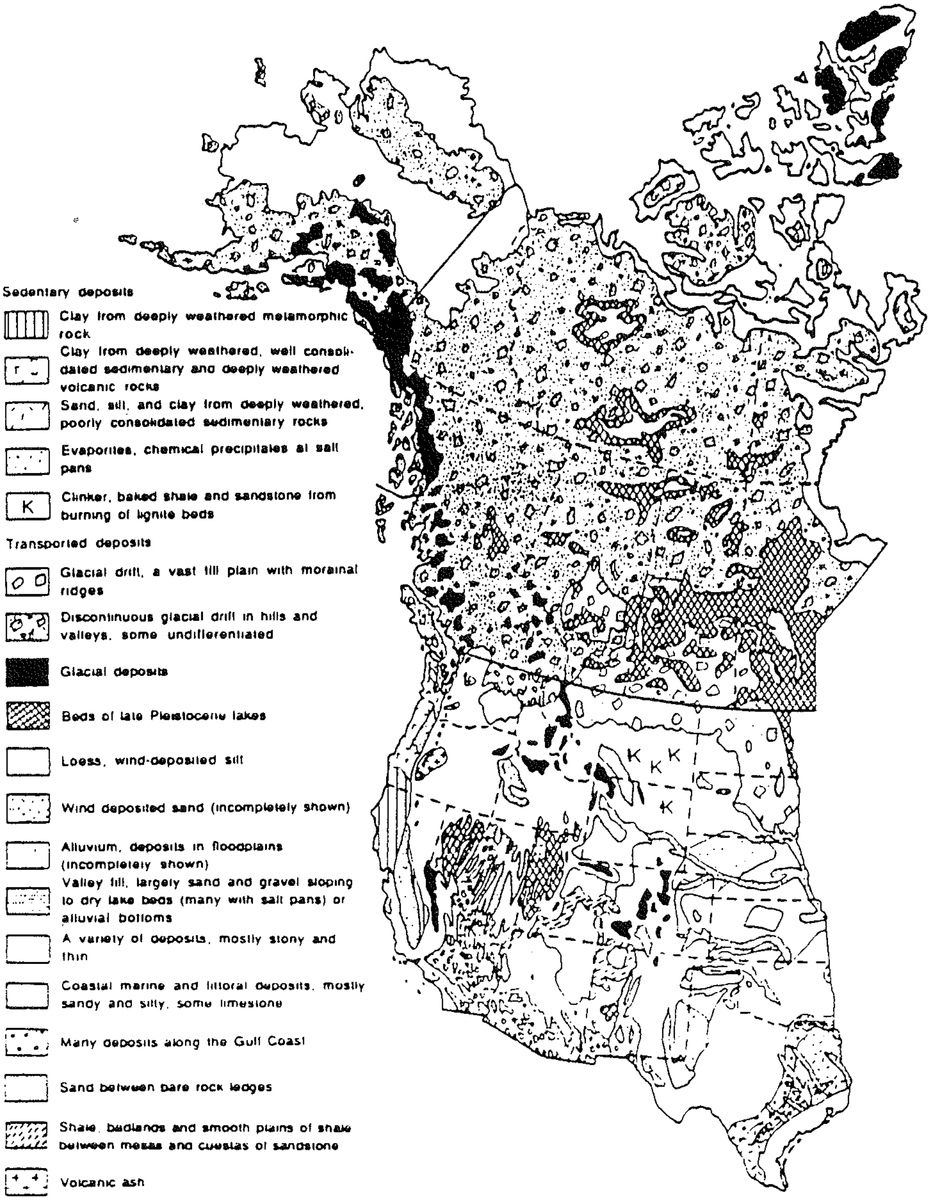

Fig. 5. Surface geology of western North America (source: Hunt 1974).

United States and north-central Mexico. It is the driest of all the North American grasslands, with annual precipitation ranging from 250 to 450 mm. The major grass genera are *Aristida* and *Bouteloua*.

Mountain grassland. This type of grassland extends across 267,700 km^2 along the eastern foothills of the Rocky Mountains. Rainfall ranges from 400 to 800 mm; the growing season is short, often less than 100 days. *Festuca* is the dominant grass genus.

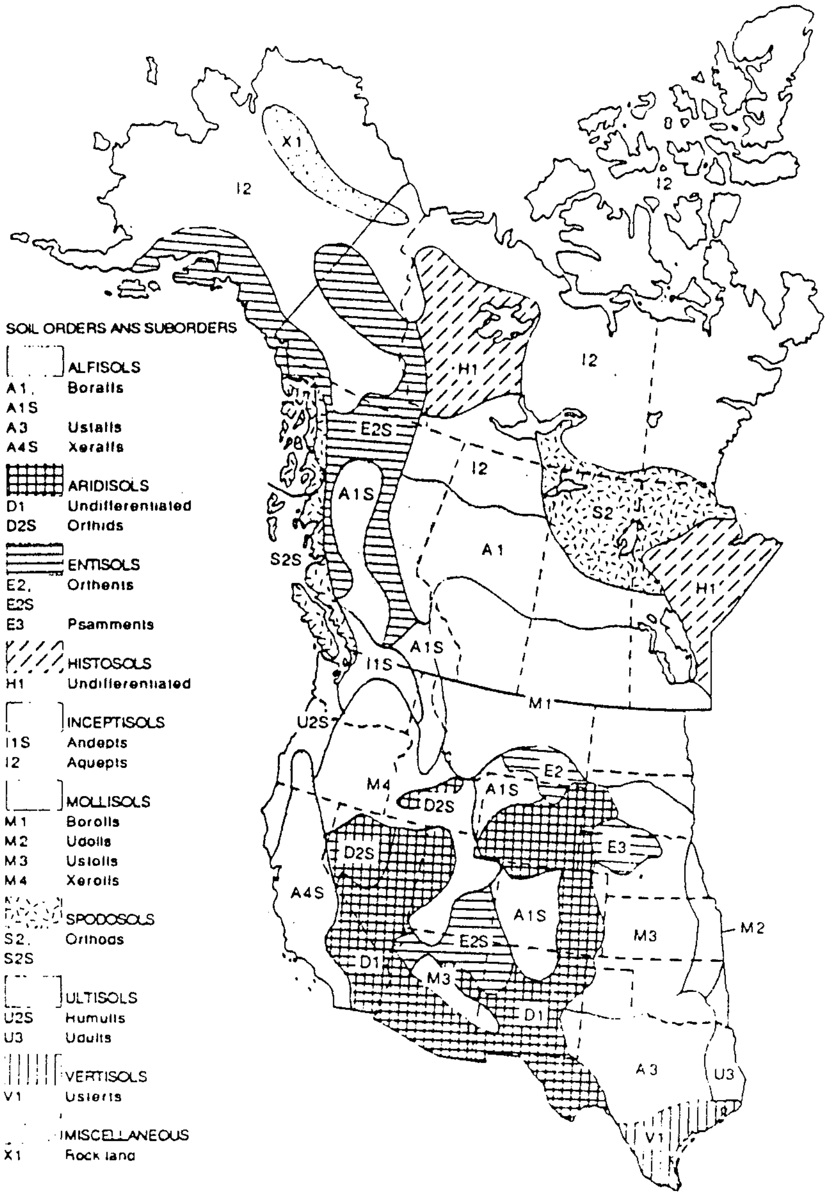

Fig. 6. Soil orders and suborders of western North America (reprinted by permission of Macmillan Publishing Company from The Nature and Properties of Soils, by Nyle C. Brady. Copyright ©1984 by Macmillan Publishing Company).

Shrub steppe. This grassland type occupies 64,700 km^2 in the arid regions of the northwestern United States where the bulk of precipitation is in the form of snow. Little rainfall occurs in the summer, so most plant growth occurs in the spring and fall. Before settlement, *Agropyron* and *Poa* were dominant; with grazing, shrubs like *Artemisia* and annual grasses (like *Bromus*) have become prominent.

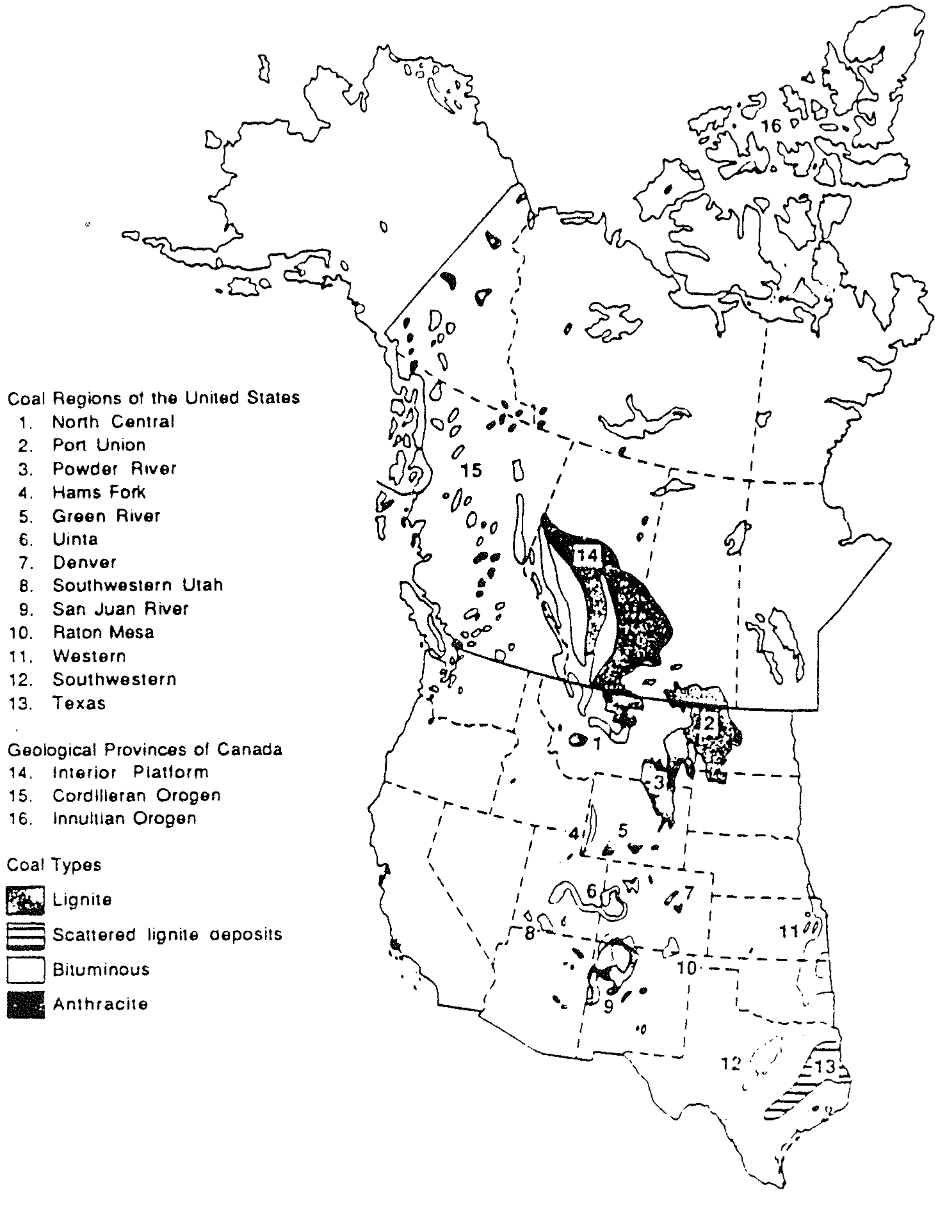

Fig. 7. Major coal-bearing regions of western North America (source: Trumbell 1975, Canada Department of Energy, Mines and Resources 1979).

Shortgrass prairie. It is dominated by grasses adapted to xeric conditions, such as *Bouteloua* and *Buchloe*. It is located on the western edge of the central Great Plains, and occupies 615,200 km^2 in the United States. Other attributes of this grassland type, along with those from mixed-grass and tallgrass prairies, are shown in Table 1.

Mixed-grass prairie. These grasslands occupy a zone of greater moisture, produc-

Table 1. Salient features of North American priaries (modified from Burton *et al.* 1988).

Attribute	Shortgrass	Mixed grass	Tallgrass
[1]Vegetation types (Sensu Küchler)	64-65	66-70	74-78, 81-82, 88
[2]Pre-settlement area, km^2	507,970	510,316	745,680
[2]Remaining area, km^2	32,910	264,070	198,710
[2]Remaining area, %	63.6	51.7	26.6
[3]Annual precipitation, cm	25-50	40-75	50-100
[3]Potential evapotranspiration (P.E.T.), cm.yr^{-1}	85-195	71-160	62-139
[3]Precipitation/P.E.T. ratio (during growing season)	0.3-0.5	0.4-0.7	0.6-1.0
Species richness, spp./km^2	30-60	50-200	150-300
Canopy height, cm	15-60	40-120	80-180
[4]Fire periodicity, years	5-10	2-7	1-3
[5]Dominant grasses	*Aristida purpurea* *Bouteloua gracilis* *Buchloe dactyloides* *Hilaria mutica*	*Agropyron* spp. *Aristida longiseta* *Bouteloua curtipendula* *Koeleria cristata* *Schizachyrium scoparium* *Stipa* spp.	*Andropogon gerardii* *Elymus canadensis* *Panicum virgatum* *Sorghastrum nutans* *Spartina pectinata*
[5]Dominant forbs	*Artemisia frigida* *Opuntia* spp. *Phlox hoodii* *Yucca* sp.	*Chrysopsis villosa* *Gutierrezia sarothrae* *Haplopappus spinulosus* *Psoralea* spp. *Ratibida columnifera* *Solidago missouriensis*	*Amorpha canescens* *Echinacea pallida* *Eryngynium yuccifolia* *Liatris punctata* *Phlox pilosus* *Ratibida pinnata* *Silphium* spp. *Solidago rigida*

Principal sources: [1]Küchler (1964), [2]Klopatek *et al.* (1979), [3]United States Geological Survey (1970), [4]Sauer (1950), Wright and Bailey (1982), [5]Weaver (1954), Weaver and Albertson (1956).

tivity, and stature east of the shortgrass prairie, and comprise 566,200 km^2 (excluding Canada). It is a transitional area between grasslands dominated by tall grasses (with more moisture) to the east and short grasses to the west. The common grass genera include *Agropyron* and *Stipa*.

Tallgrass prairie. Often referred to as the true prairie (Risser *et al.* 1981), these grasslands occupy the eastern-most region of the North American grasslands. Tallgrass prairie encompasses roughly 573,500 km^2 in the United States and has the highest rainfall and greatest north-south diversity of all the grassland types. It often borders on forested areas. The most typical genera include *Andropogon*, *Panicum*, and *Sorghastrum*, all very tall, exceeding 120 cm and sometimes reaching 3 m in height.

Combined, these natural grasslands once occupied 3.95 million km^2 (19.2 percent) of continental North America (Stevenson 1972). The grassland landscapes were level or gently rolling. They had deep soils high in organic matter, and were thus subject to massive agricultural conversion at the time of European colonization in the 1800s (Iverson 1988). The extent of conversion to agriculture was proportional to native productivity and diversity. Approximately 92 percent of the original shortgrass prairie still existed in the mid-1970's, whereas only 36 percent of the mixed grasslands

Table 2. General relationships (high and low) of herbage yields to precipitation (kg ha^{-1} cm^{-1}) in North American grasslands (from Cook and Bonham 1977).

Vegetation	Location	Herbage Yield	
		High	Low
Semidesert grass-shrub	Arizona	7	2
Semidesert grass-shrub	New Mexico	21	16
Salt desert shrub	Utah	19	9
Palouse prairie	Oregon	25	20
Sagebrush-grass steppe	Idaho	30	27
Mixed-grass prairie	Kansas	79	60
Mixed-grass prairie	North Dakota	77	44

and 15 percent of the tallgrass prairies remain (Klopatek *et al.* 1979). As an example of the extent of tallgrass conversion, in Illinois only 0.0118 percent of the original 8.4 Mha remain (White 1978, Iverson and Risser 1987). Illinois prairies were discovered to be viable croplands in 1830 with the introduction of the moldboard plow. By the end of the decade, 96 percent of the prairie had been converted (Telford 1926). It is not surprising, therefore, that prairie restoration has been gaining importance in the Midwest; the first restoration project began in 1936 at the University of Wisconsin at Madison (Green and Curtis 1953, Schramm 1970, Burton *et al.* 1988).

Grassland ecosystem properties

Grassland ecosystems have many characteristics which distinguish them easily from other biome types (Risser *et al.* 1981, Burton *et al.* 1988). Critical aspects for grassland ecosystem maintenance are the system's adaptation to drought, fire, and grazing (McNaughton *et al.* 1982, Risser 1985).

The influence of climate on the maintenance of grassland is indisputable. Holdridge (1947) noted that a grassland climate exists when the average total precipitation ranges from 250 to 500 mm per year and the precipitation to evapotranspiration ratio ranges from 1 to 2. Clements and Shelford (1939) and Borchert (1950) also reported on the close correlation between the North American climate and the location of the prairies. Weaver and Albertson (1956) reported that the prairie boundaries exhibited a pronounced eastward shift during the extended drought of the 1930's.

The total amount of precipitation during the previous year and the amount that falls during the growing season are the best determinants of grassland plant growth and yield. Thus, many studies have examined the precipitation-yield relationships for several rangelands in North America (*e.g.*, Coupland 1950, Smoliak 1956, Whitman and Haugse 1972, Cook and Bonham 1977). Expectedly, reports show high forage yields in the years of high annual precipitation and low forage yields in years of low annual precipitation. The data of Cook and Bonham show that, in general, forage yield is high per centimeter of precipitation for zones with more precipitation such as the mixed-grass prairie and least for some of the semi-desert areas with low precipitation (Table 2).

Effects of precipitation on yields of herbage of native range in the northern Great Plains vary from a few to about 80 kg ha^{-1} cm^{-1}. Typical values of yield per unit of precipitation are 20 to 30 kg ha^{-1} cm^{-1} in the drier regions of northern Great Plains and up to double these values in the wetter ranges (Table 2). Water use efficiency is improved by fertilizer treatment. Values for reseeded pastures are higher, and values for fertilized and reseeded pastures are higher yet. The phenology and seasonality of plants of grassland regions afford them added adaptability to precipitation and temperature regimes. For example, Whitman and Wali (1975) reported that most cool-season species in the mixed grass prairie of North Dakota start growth in late April or early May and by late July have reached maximum height. The sedges and *Poa* spp. began their growth first and mature in early June. *Agropyron smithii* and the *Stipa* spp. achieved maximum leaf length by 1 July. *Bouteloua gracilis* began growth later than the other species and reached its maximum leaf length by 1 August. The ending of the growth season was controlled more by the exhaustion of available moisture than by low temperatures.

However, grassland response to precipitation can be variable, and as precipitation increases, the relative yield response decreases toward some asymptotic value. The precipitation level at which this occurs is based on many factors including general climate, species composition, and the proportion of cool and warm season grasses and C_3 and C_4 species in the vegetation.

Survival of grassland plants, however, is assured by several physiological- morphological adaptive strategies to overcome drought (Risser 1985). These include the closing of stomata, early curling, C_4 metabolic pathway, dormancy, rapid root growth, and delayed germination.

In addition to climate, fire has had a profound influence on the maintenance of the prairies. Assessment of original land survey records prior to European colonization in the early 1800's revealed much larger prairie patches on the windward side of river valley bottoms relative to the leeward sides in Illinois (Iverson and Risser 1987). Frequent, large prairie fires set by lightning, or by Indians to drive game (Sauer 1950), killed or repressed most of the juvenile trees and shrubs. On the other hand, grassland plants have rapid regrowth potential following fire from subsurface perennating organs. When systems are not excessively stressed already, fire normally stimulates the productivity, vigor, and diversity of the native grassland flora by removing shade and ground litter, thereby allowing the soil to warm up rapidly in the spring to take advantage of the higher moisture reserves available. Insufficient fires on today's remnant prairie patches have led to the invasion of woody species, especially in those areas where the climate could normally support the growth of trees.

Adaptations of prairie plants to grazing pressure includes the intercalary meristems which permit continuous regrowth, various antiherbivore devices such as toxic compounds, low palatability and coarse seed stalks, increased photosynthesis, and allocation of assimilates to regrowing tillers following grazing (Risser 1985). Grasslands have other distinctive properties as well. They tend to have more biomass below ground than above ground; rooting depths up to 5 m are not uncommon (Weaver 1954). Prairie grasses also have tremendous production capacity under all but the most adverse conditions. The above-ground productivity is typically more than 20 percent, greater than the rate of decomposition; thus, litter accumulates. If this litter is not reduced by grazing or fire, productivity will decline and biological invasion by woody species will be promoted. Grasslands are also well adapted to cycling of nutrients (Risser 1985). Rapid nutrient uptake occurs when moisture and nutrients are adequate, and recycling and storage of nutrients can occur internally.

Table 3. Land utilized and reclaimed by the mining industry in the United States, 1930-1971 (from Paone *et al*. 1978),

	Area in ha, by type of commodity							
	Metals		Nonmetals		Fossil fuels		Total	
Type of use	Utilized	Reclaimed	Utilized	Reclaimed	Utilized	Reclaimed	Utilized	Reclaimed
Surface mining excavation	58,700	7,040	429,000	102,000	391,000	290,000	879,000	399,000
Overburden and refuse disposal from surface mining	49,800	2,130	118,000	52,200	129,000	108,000	297,000	162,000
Subsidence and disturbance from underground mining	4,940	720	1,850	40	35,600	1,620	42,400	2,400
Disposal of refuse from underground mining	8,860	610	840	70	67,200	8.090	76,900	8,770
Disposal of wastes from milling and processing	89,400	7,000	81,300	9,430	12,900	2,620	184,000	19,100
Total	212,000	17,500	631,000	164,000	635,000	410,000	1,480,000	591,000

Excludes oil and gas operations

Anthropogenic Disturbances Associated with Coal and Mineral Removal

Extent of land disturbed in the United States

Of the total land area in the conterminous United States, approximately 1.5 Mha (0.2 percent) was affected by various mining activities from 1930 through 1971 (Paone *et al.* 1978) (Table 3). Approximately 40 percent of the area was reclaimed to some extent during that period. These activities included mines, quarries, pits, mills, and coal preparation plants, but not disturbances associated with petroleum and natural gas activities. We know of no reliable U.S. estimates of acreages disturbed by oil and gas activities. In Illinois, as an example, the estimates of lands critically damaged from exploration of oil and gas (especially brine contamination) range from 11,300 to 15,400 ha (Coleman and Crandall 1981). The area that has been disturbed by coal and mineral extraction may appear small (Table 3), but the drastic and conspicuous nature of the activity, coupled with the magnified environmental degradation associated with unreclaimed sites, dictates that we must strive for successful reclamation everywhere possible. If all of the estimated surface-minable areas in the United States were mined, 18.6 Mha (2 percent) would be disturbed (Barrows 1975).

During the period 1930-1971 (before the promulgation of state reclamation laws and the 1977 Federal Surface Mining Control and Reclamation Act), about 40 percent of the land disturbed was for the production of bituminous coal (Paone *et al.* 1978). The remaining 60 percent was disturbed to produce various non-metals and metals (excluding oil and gas): sand and gravel (18 percent), stone (14 percent), clay (5 percent), copper (5 percent), iron ore (3 percent), phosphate rock (2 percent), and other minerals (13 percent). Mining procedures differ, and these differing methods of extraction lead to variations in reclamation challenges and in final landscape appearance. Surface mining includes open pit (open cast), strip, dredging, and hydraulic mining. Open pit mining includes quarries to produce limestone, sandstone, marble, and granite; pits to produce sand and gravel; and large iron or copper excavations. These operations usually disturb relatively small surface areas due to the thickness of the material, but they leave large holes in the landscape, which are best reclaimed to aquatic or wetland systems. Ore mines also leave trailing spoils. Strip mines, which employ either area or contour stripping depending upon the ruggedness of the terrain, are used to produce coal. Initial rehabilitation usually means bulldozing to approximate the original contour of the land. Dredging uses a suction apparatus or mechanical device that brings up material from stream beds in search of gold. It produces tailing pits. Hydraulic mining was used extensively in the past to produce gold. Water jets were used to break up the ore and separate it from the metal; this also produced abundant water piles. With underground mining for coal, the Longwall Method results in roof collapse (so some surface subsidence will occur), whereas the Room and Pillar Method leaves pillars of coal and timber to prevent subsidence. These methods generate disturbances via subsidence, disposal of mining refuse, and disposal of processing wastes (Table 3). Oil and gas extraction leads to numerous small patches of disturbance. The most serious problem is the accidental (or deliberate) contamination of soils by brine. Oil shale extraction, however, has the potential for large-scale land disruption (Davis 1978).

Many rehabilitation problems are common regardless of the commodity extracted (*e.g.*, erosion, low fertility) (Hill 1978). However, some commodity extractions result in unique problems that must be addressed individually. For example, the mining of uranium often leaves tailings that must be specially treated (Federal Water Pollution Control Association 1966). Revegetation of mine tailing ponds require special techniques (Nielson and Peterson 1978, Nawrot 1981), as does revegetation of phosphate mines in Florida (Farmer and Blue 1978, Bromwell and Carrier 1983), and some metallic mines (Ripley *et al.* 1978).

Because of the differences in extraction methods (open pit vs. strip mining vs. waste-generating activities), and because of the historical variation in legal requirements, some commodity types had a better reclamation record than did others during 1930-1971. For example, 410,000 of the 635,000 ha (65 percent) disturbed by coal mining were reclaimed during that period. On the other hand, only 164,000 of the 631,000 ha (26 percent) disturbed by non-metal mining were reclaimed (Table 3) (Paone *et al.* 1978). Between surface- and underground mining for coal, the areas affected are much greater with surface mining, but the reclamation record is much better relative to underground mining (Table 3). Of course, under current legal requirements, nearly all new areas disturbed by mining will have to be reclaimed, but the backlog is still with us. Discussion of this backlog of disturbed sites, referred to as abandoned mined lands, follows.

Rehabilitation of Abandoned Areas

Extent and nature of the problem

We concentrate here on abandoned coal mines, defined as 'those which were mined for coal or which were affected by such mining, waste banks, coal processing, or other coal mining processes, and abandoned or left in an inadequate reclamation status prior to August 3, 1977, and for which there is no continuing reclamation responsibility under State or Federal laws [1977 Surface Mining Control and Reclamation Act (hereafter SMCRA), Section 404].

Estimates of abandoned mine land (AML) under this definition vary widely for the United States (Nawrot *et al.* 1982, United States National Research Council 1986). For example, it has been estimated that 800,000 ha (including non-coal mined lands, only surface mined) needed various degrees of treatment to alleviate a range of environmental damage, both on- and off-site (United States Department of the Interior 1967). Other such estimates are lower: the Soil Conservation Service estimated 444,000 ha of land needed reclamation but is not required by any law (United States Department of Agriculture 1979a), whereas the U.S. Bureau of Mines estimated 396,000 ha had been abandoned and adversely affected by past mining activities (Miller and Johnson 1979). The discrepancies in estimates lie in the definitions of lands included, and the methods employed to obtain the estimates. The above estimates are for the United States alone. Canada was estimated to have 52,600 ha of land disturbed by mining in 1969. Of the 14,200 ha disturbed by coal mining, less than 1,000 ha were reclaimed (Rabbitts *et al.* 1971). Additional data are provided in Thirgood (1978) and Watkin (1979).

Title IV of SMCRA was enacted to correct problems of land mined for coal and abandoned prior to 1977. Through a tax levied on each ton of coal mined, an estimated $3.3 billion were to be generated for this purpose between 1977 and 1992 (United

Table 4. National inventory data: state requests and Office of Surface Mining (OSM) entry into standardized data base (source: United States Department of the Interior 1983a).

Problem Type[1]	State-submitted	OSM-approved
A. Mine Facility-Related Safety Hazards		
1. Vertical openings	927	332
2. Portal	1605	277
3. Hazardous equipment or facilities	930	157
B. Other Mine-Related Safety Problems		
4. Dangerous highwall	598	175
5. Dangerous pile of embankment	233	42
6. Dangerous impoundment	232	12
7. Surface burning	149	37
C. Water-Related Impacts		
8. Dangerous slide	190	97
9. Flooding or ground saturation	434	329
D. Subsidence		
10. Subsidence	397	120
E. Public Health Problems		
11. Polluted water: agriculture or industry	188	6
12. Polluted water: human consumption	164	13
13. Industrial or residential waste	268	36
F.Other Problems		
14. Gases from underground burning	104	11
15. Hazardous recreational water body	153	32
16. Hazardous or explosive gases	21	4
TOTALS	6620	1680

[1]These data represent priority 1, 2 and 3. Problem areas are not the same as problem areas in number or definition.

States National Research Council 1986). Because it has been estimated that at least $25 billion would be needed to correct all problems, a priority system was set up for allocating funds. Priority 1 includes those sites that need rehabilitation to protect the public's health, safety, and general welfare, and property from extreme danger of the adverse effects of coal mining practices. Priority 2 also protects the health, safety, and general welfare of people and property but does not include 'extreme danger' status. For Priority 1 sites, the distinguishing characteristic was determined to be 'harm reasonably expected to occur within a year' (United States National Research Council 1986). Priority 3 problems involve the rehabilitation of lands and water resources previously degraded by coal mining.

A national inventory was conducted in 35 states and four Indian tribe lands to gather information on the number and extent of the three types of AML so that efficient allocation of funds could be made (United States Department of the Interior 1983a). The inventory now consists of a database describing 3,960 problem sites as determined by individual states; 1,373 qualified as Priority 1 or 2 by the Office of Surface Mining (OSM) standards. The remaining 2,587 problem sites have been designated as Priority 3 areas; the Priority 3 list is by no means exhaustive. A list of

OSM-approved problem types is given in Table 4, most of these are from Priority 1 or 2 areas.

Natural grassland revegetation of abandoned mines

Several studies have been conducted to investigate vegetation and soil development following a major disturbance. These studies form the foundation upon which mechanisms of succession have been examined. Considerable knowledge of succession has come from studies of areas after glacial retreats (Crocker and Major 1955, Stevens and Walker 1970), mudflows (Dickson and Crocker 1953a, 1953b, 1954), alluvial deposits (Wright *et al.* 1959), and abandoned old fields (Whitman *et al.* 1943, Keever, 1950, Egler 1954, Bazzaz 1968). Early studies on surface coal-mined spoils in Illinois were conducted by McDougall (1918) and Croxton (1928), who suggested that the mined sites provided excellent opportunities for the study of plant succession. Other studies of natural revegetation on mined sites contributed further knowledge in Indiana (Byrnes and Miller 1973), Illinois (Ashby 1964, Thomas and Jansen, 1985), Pennsylvania (Bramble and Ashley 1955, Schramm 1966, Schuster and Hutnik 1987), Oklahoma (Gibson 1982, Johnson *et al.* 1982, Gibson *et al.* 1985), and Iowa (Glenn-Lewin 1979). These studies were generally conducted in locations where the potential or 'climax' vegetation is dominated by tree species, and where the excavated parent materials are predominantly acid and low in bases (Leopold and Wali 1990).

The studies on soil/vegetation development in areas with potential grassland vegetation are more recent (see for example, Wali 1973, 1975) and are discussed later. Mackey and DePuit (1985) studied the natural revegetation on spent oil shale up to 60 years in age, and found large differences in composition compared to unmined areas even after 60 years.

Wali and Freeman (1973) studied the soil-natural vegetation complex on abandoned coal mines ranging in age from 1 to 53 years (and unmined areas for comparison) across a broad geographic region in western North Dakota. Mined sites were found to have a generally higher pH, electrical conductivity (EC), silt and clay fractions, concentrations of soil sodium (Na), magnesium (Mg), total phosphorus (P), sulfur (S), copper (Cu), and pioneering plant species with halophytic characteristics. On the other hand, organic matter (OM), species diversity, and potassium (K) and manganese (Mn) concentrations were higher on the unmined sites. Even the oldest (53 years) site had only one-half the species richness of the unmined sites. This study emphasized the need for a site-specific, ecologically-based approach to the rehabilitation of these areas, with emphasis on the role of topographic and edaphic variables in understanding the processes of soil and vegetation development over time.

Statements on successional sequences were limited because of inconsistent conditions of the sites at time zero. Most often, variations exist in parent material which greatly alters the course of succession. The study by Wali and Pemble (1982) came the closest to assessing true succession following mining in the grassland regions of North Dakota. They were able to assume relative similarities of regional climate, fire history, and soil parent materials. According to Jenny's (1941) and Major's (1951) state-factor approach, soil and vegetation development is a function of climate, organisms, relief, parent materials, and time. Major (1974) added "fire" to these five factors as a variable influencing vegetation development. Wali and Pemble (1982)

Table 5. Trends in selected soil characteristics at naturally revegetated and reclaimed sites in North Dakota (from Wali and Pemble 1982, and Iverson and Wali 1982a).

Age after mining	EC[1]	Ca[2]	Mg[2]	SO_4[2]	OM[3]	N[4]	P[5]	pH[6]	Percent clay[7]	Number of Species[8]
					Abandoned mine land					
Year 1	3.3	1.3	0.9	765	1.9	0.05	2.2	8.1	28.0	26
Year 7	1.8	0.7	0.3	366	2.0	0.05	1.9	8.2	32.0	37
Year 17	1.1	0.6	0.2	136	2.0	0.07	2.8	8.3	30.0	52
Year 30	1.0	0.5	0.1	58	1.7	0.09	2.9	8.2	30.0	43
Year 45	1.0	0.5	0.1	33	2.4	0.10	4.2	8.3	29.0	68
Unmined	1.2	0.5	0.2	25	5.0	0.26	5.6	8.3	24.0	114
					Reclaimed mine land					
Year 1	3.1	1.6	1.8	2265	2.4	0.11	15.4	7.8	30.0	13
Year 2	2.1	1.0	0.8	1273	2.4	0.12	13.2	8.0	28.0	19
Year 3	2.3	1.1	0.9	1566	2.9	0.13	5.1	7.6	26.0	14
Year 4	1.2	0.4	0.2	402	3.7	0.20	13.1	7.9	24.0	24
Unmined	0.3	0.2	0.1	39	3.5	0.18	4.5	7.4	15.0	45

[1]dS/m in saturation extracts; [2]water soluble from saturation extracts, ppm; [3]Walkley-Black method, %; [4]total Kjeldahl N, %; [5]Olsen's method, ppm; [6]hydrometer method, %; [7]number of species in 33, 0.5 x 2 m quadrats (abandoned) and in 50, 0.5 x 0.5 m quadrats (reclaimed); [8]number of species in 33, 0.5 x 2 m quadrats (abandoned) and in 50, 0.5 x 0.5 m quadrats (reclaimed).

were thus able to present the changes in soil and vegetation development over a 45-year period as a function of time and topography. Adjacent unmined areas were selected for comparison.

They sampled AML sites 1, 7, 17, 30, and 45 years of age, and the unmined controls. They also sampled lower, upper, and crest positions on each of the eight cardinal compass directions. Vegetation was sampled for presence and percent cover, and soils were sampled at three depths (0-10, 10-30, and 30-70 cm). A total of 156 species were found, ranging from seven species on the 1-year-old site to 114 species on the unmined site. The 45-year old site had 68 plant species, or 60 percent of that on the unmined site. The plant species were related to slope aspect and position patterns by constructing 'target' diagrams that show the cover estimate in the 17 slope positions for each plant species. With the unmined site data it is apparent that plant species sort out on slope aspect preferences. The 'target' diagrams also aid in viewing successional species replacements over time, as has been done for a number of species. Stand-environmental complex ordinations encompassing 53 variables showed topographic and site age variables to be the most important. In addition to the trends in vegetation patterns, Wali and Pemble (1982) found a large number of trends in spoil/soil properties over time. Water-soluble cations (Na, Ca, Mg, and K) and EC decreased with age due to soil-leaching processes (Table 5). On the other hand, OM, N, P, and replaceable K tended to increase with time, and calculations were made of rates of accumulation: organic carbon (13.1 g/m^2 /yr); N (2.5 $g/m^2/yr$); P (0.01 $g/m^2/yr$); and K (0.49 $g/m^2/yr$). Nitrogen accumulation was more pronounced on northerly exposures compared to southerly (drier) exposures. Carbon-nitrogen ratios showed the widest range for 1-year-old sites (9-42), but 70 percent of the 45-year-old sites showed values below 15, which were comparable to the unmined mixed-grass prairie. Several other soil properties (sulfate concentrations, sodium adsorption ratios, and water-soluble Sr) showed decreased values with age, while others (EDTA-extractable Si and Al) an increase with age. This study thus thoroughly documented species/spoil trends with time, and emphasized the importance of topography in these processes. Comparisons were made to the three pathways of succession suggested by Connell and Slatyer (1977). It was determined in this study that all three pathways (facilitation, tolerance, and inhibition) were operating simultaneously.

Impediments to Rehabilitation of Abandoned Mines

Plant growth depends on several environmental factors (*e.g.*, water, nutrients, temperature, and light). In a highly disturbed system, additional factors (altered pH, texture, salinity/ sodicity, soil stability) influence plant survival and growth. Here we discuss the factors having the greatest influence in the reestablishment of vegetation.

Water. That water availability is the most critical factor to reclamation in the semi-arid West, was recognized by the National Academy of Sciences (1974). The availability of water to a plant depends on the amount held per unit volume of soil, and on the depth to which the plant's roots can penetrate. Therefore, the important factors are soil texture and OM content (water-holding capacity), slope angle, surface roughness (water infiltration), bulk density or presence of hard-pan soil (root penetration), and slope aspect and latitude (solar intensity). Abandoned mines often have high slope angles, high solar intensity (on southerly and westerly exposures), and have low rates of infiltration such that moisture deficits are exacerbated. For example, Szafoni *et al.* (1988) found AMLs in northern Illinois to have water-potential readings as low as -4.0 MPa, a value of -1.5 MPa is generally cited as the permanent wilting point (Fischer and Turner 1978).

Acidity and potential acidity. Whereas plants usually grow at optimal rates under neutral conditions, abandoned mines have either a high or a low pH. For example, in a survey of 35 abandoned mines in North Dakota, the soil pH ranged from 2.3 to 9.1; most were alkaline (Nicholson *et al.* 1984). In general, the higher rainfall levels permit more pyrite oxidation in eastern spoils. Studies of AMLs in northern Illinois (Iverson *et al.* 1983, Grunwald *et al.* 1988), originally at the eastern edge of the tall-grass prairie, showed excess acidity with the spoil pH ranging from 3.0 to 4.0.

Acid soils can cause dysfunctions in plant growth: impaired absorption of P, Ca, Mg, and K; increased availability of Al, Mn, Fe, Cu, Zn, and Ni (often in toxic proportions); and creation of unfavorable biotic conditions, such as reduced N fixation and mycorrhizal activity and increases in fungal pathogens (Black 1968, Tucker *et al.* 1987). On the other hand, soils with a high pH can cause: impaired soil release of Fe, Mn, B, P, Cu, and Zn; increased availability of Mg, Ca, S, and K; and increased infection by fungi (actinomycetes and bacteria).

Fertility and toxicity. Most mine waste is low in N and P (Barrett *et al.* 1979). For adequate and long-term plant community regeneration an active biological N cycle is necessary, which requires adequate C and N pools (Reeder and Sabey 1987); the mining process disrupts the N cycle. Since the system is not stabilized, nutrient leaching is also a problem. Macronutrients (Ca, K, N) and micronutrients (B, Cu) will leach at a low pH, further reducing the fertility of the site. Copper and Mo (Neuman *et al.* 1987), B (Barth *et al.* 1987), Se (Fisher *et al.* 1987), and Cd and Zn (Safaya *et al.* 1987) become troublesome (deficient and/or toxic) in abandoned mine systems where imbalances occur within a wide variation of pH. Care must be taken to insure long-term nutritional stability.

Salinity and sodicity. The electrical conductivity (EC) of the soil solution is a measure of the water-soluble salt content or salinity of the soil. The major adverse effect of elevated soil salinity is to reduce the availability of soil water to plants through a direct relationship with osmotic potential (Jurinak *et al.* 1987). Salt-tolerant plant species grow in soils with readings above 3.6 dS/m (in 1:1 extracts), but plant growth in general may be reduced at values as low as 1.8 dS/m (Bradshaw and Chadwick 1980). Salt buildup can be a particular problem in semiarid areas where leaching of the soil is low, or where the accumulation of salts is near the surface.

Sodic soils are those with an exchangeable sodium percentage (ESP) > 15 with or without appreciable salinity. Soils with ESP > 15 usually have enough exchangeable Na to interfere with the growth of most plants, and the pH is usually alkaline. As ESP increases, soil particles become dispersed and are therefore less permeable to water. As a result, the soil exhibits poor structural stability. The sodium adsorption ratio (SAR) is a measure of both the concentration and the composition of the salts in soil solution and gives a good indication of the likelihood of successful plant establishment (Wali and Sandoval 1975). It is the square root of the ratio of Na to Ca and Mg, and it is highly correlated with ESP (Richards 19549). In general, spoil materials with SAR exceeding 12 is deemed unsuitable as a plant substrate in reclamation practices (Wali and Sandoval 1975, Carlstrom *et al.* 1987).

Temperature. Soil temperature is affected by many factors: air temperature, intensity quality, and duration of radiant energy, precipitation and evaporation, topography, soil color and thermal conductivity, and surface cover (Nielsen 1974). Barren spoils, especially the dark shales common on mine sites, lose little heat through convection and evaporation, with a consequential rise in soil temperature. As the barren soil dries out, evaporation decreases and the surface temperature continues to rise. Temperatures as high as 67 °C have been recorded on dark mine waste (Deely and Borden 1973). High surface temperatures are obviously detrimental to plant (especially seedling) growth.

Soil structure and compaction. Spoil materials have textures and structures quite different from native soils. Spoil materials generally contain little organic matter and have little microbial activity (Allen 1985). Depending on the mining procedure used and the removal of waste material, the site can be either quite homogenous or relatively heterogenous. Heavy equipment traffic contributes to spoil compaction with the consequential reductions in soil porosity, water infiltration, ion diffusion rates, gas exchange, and root penetration (Warncke and Barber 1971, Bradshaw and Chadwick 1980).

Some AML site studies

In elucidating some specific problems associated with abandoned mine reclamation, Szafoni *et al.* (1988) summarized the vegetation and spoil characteristics of eight grassland AML sites, four each in North Dakota and in northern Illinois. The North Dakota sites resulted from surface mining activity 20 to 40 years ago, and the Illinois material consisted of roof rock and underlying clay waste resulting from underground mining activities from 1875 to 1930 (Nicholson *et al.* 1984, Grunwald *et al.* 1988, Szafoni *et al.* 1988). The sites reported on here range from very poor, almost non-existent vegetative cover to a reasonable vegetative cover.

North Dakota. The site (New Salem) with the worst revegetation success was characterized by excessive sodicity, elevated pH, high saturation percentage (high clay content), and very low OM, N, and P. The Fritz site also was poorly vegetated and was fairly atypical for North Dakota; the site was quite acidic (pH 3.77) rather than alkaline. It had adequate P, but was very sandy, compacted, and deficient in N. The Davenport site was well revegetated but was still in an early stage of succession because it retained a high proportion of annual plant species. It was also low in OM. The Velva site had the highest revegetation success and fairly high cover and diversity. It seemed to have acceptable levels of most spoil characteristics except for very low levels of P.

Illinois. Of the four sites in Illinois, the revegetation success was as follows: Spring Valley < Standard < Ladd < Wenona. All of the sites were acidic, with Al toxicity a real possibility on at least the three worst sites. The Spring Valley site had the highest Al and salinity and the lowest pH. Measured soil water potential readings indicated levels below -2.5 MPa during much of the 1982 growing season (Grunwald *et al.* 1988). The Standard site was also poorly vegetated, though better in acidity relative to Spring Valley, it had very low total N. The Ladd site had an estimated 20 percent vegetative cover and was slightly more hospitable in terms of pH, N, P, and K relative to other sites. Finally, the Wenona site had markedly better revegetative success and its spoil conditions were much better for pH, lime requirements, N, K, Ca, and Al.

Water availability was one of the main problems in both the North Dakota and Illinois sites. At the North Dakota sites, steep slopes, high Na, and low late-summer rainfall caused extremely dry conditions. At the Illinois sites, even steeper sheet- and gully-eroded slopes prevented adequate water infiltration. Acidity problems were much more prevalent in Illinois, while sodicity/salinity problems were largely a North Dakota problem. The minimal availability of nutrients restricted plant growth in both states. Nitrogen and P deficiencies were common to most sites, as was very low organic content and the lack of an established N cycle. Al toxicity was frequently a problem for sites with a pH of less than 4.0.

Saskatchewan. Jonescu (1979) found spoil bank slopes in the mixed-grass prairie region in southeastern Saskatchewan were only 50 percent or less vegetated even after 40 years. The dominant plant species were exotic pioneers; the north and east slopes had significantly more cover than the south- and west-facing exposures. Moisture accumulated in the interridge zones and thus exhibited greater cover, stability, richness, and successional advances than did the ridge slopes. Jonescu (1979) also found no significant vegetation differences with age among the slopes but did note significant differences among the interridge zones. Anderson (1977) studied soil development in the same region of Saskatchewan and determined soluble salts had leached in 40 years and that C and N had built up to some extent. He estimated that the C and N equilibrium would not be reached for 250 to 350 years.

Montana. Semiarid mixed grasslands in eastern Montana, revegetated mined sites from several months to 50 years old were studied (Schafer and Nielson 1979, Sindelar

1979). Older mine sites with sandy loam spoil and heavier grazing were considerably less successionally advanced than those sites having spoil with more silt and clay (*i.e.*, adequate water-holding capacity). Diversity and richness on 50-year-old sites resembled that of undisturbed sites when soil properties approximated those of native soils. However, when spoils were unfavorable, even 50 years of succession did not produce a vegetative cover and composition similar to unmined sites. They also verified that some early successional stages associated with soil formation could be bypassed by some reclamation practices, including the addition of topsoil, fertilizer, mulch, and mixtures of various plant species.

Remedies for Grassland Establishment on Abandoned Mine Lands

The case studies discussed above show the major problems associated with abandoned mine rehabilitation. We now focus on some of the methods used to combat these barriers to revegetation. These measures include: erosion control and water conservation, restoring fertility, organic matter regeneration, alteration of pH, salt management, and plant selection.

Erosion control and water conservation. High slope angles are very common in abandoned mines. The reduction of slope angle by earth-moving equipment will stabilize spoil banks, prevent slumping, and greatly reduce sheet, rill, and gully erosion. Erosion control and consequential increased infiltration of water will be accompanied by a reduction of overland flow. Sheet erosion, coupled with gullies, results in 10 times the soil loss of sheet erosion with minor rills (Komura 1976). Slope angle and length reduction and/or contour drain installation can be utilized to prevent gully erosion (Joy 1985). The reshaping of mine wastes, however, is extremely costly because of high amounts of spoil moving, and because additional land must be obtained to store the excess material. For example, the Illinois Abandoned Mine Land Reclamation Council has been reclaiming abandoned mine waste piles at a cost of nearly $1 million each (Keener, personal communication), most in earth-moving costs.

Several surface modifications of the spoils also result in increased moisture collection and retention. Judicious placement of water-harvesting furrows (Scholl and Aldon 1979), even large rocks or plastic condensation traps (Biggens *et al.* 1985), improve survival and growth of targeted perennial plants. Small surface modifications, such as furrows, pits, and soil ridges, have also increased grass production due to improved water infiltration, snow trapping, and reduced evaporation (Schuman *et al.* 1987). The addition of mulch, OM, submerged burlap, and other types of physical or chemical stabilizers is very effective in reducing erosion and increasing infiltration (Heede 1975, Glover *et al.* 1978, Plass 1978, Voorhees 1986).

Organic matter. As mentioned earlier, the addition of OM greatly increases infiltration. For example, 6 tons of straw per ha applied on the surface of bare soil increased infiltration 3 to 4 times that of the bare-soil control (Joy 1985). Organic matter also adds a high amount of nutrients to the depauperate spoils. The addition of sewage sludge is also highly beneficial in restoring organic C, N, P, and K (Holderson and Zenz 1978, Sopper and Kerr 1981, Sopper *et al.* 1982), even to the point of becoming agriculturally productive again. At a site in Fulton County, Illinois, for example, sewage sludge from the city of Chicago was incorporated into the soil from

1972 to 1979; the land is currently in row-crop agriculture (Peterson *et al.* 1982). Other organic materials from waste products, such as bark, chicken manure, peat, and ground-up municipal waste, are also beneficial in adding nutrients and organic matter to the soil (Bradshaw and Chadwick 1980, Alderdice *et al.* 1981). The nutrient and organic matter composition of some of these materials are given in Bradshaw and Chadwick (1980).

The application of available topsoil from adjacent areas is also very beneficial in restoring the productivity of on a mined site. The organic matter, microbial populations, seed banks, and nutrients present in topsoil constitute a buffer against the extremes of adverse spoil material properties, and topsoil rapidly increases the rate of rehabilitation. Even a thin cover of topsoil (ca. 15 cm) applied to the surface of toxic spoils, when used with adequate drainage systems, is highly successful (Drake 1983). The cost, however, is often prohibitive, especially on large areas.

Fertility and microbial restoration. The addition of organic materials helps restore nutrient conditions, but it is desirable to add chemical fertilizers to bolster the nutrition level. Many fast- and slow-release fertilizers are available commercially to supplement NPK levels in the spoil. Careful analysis of micronutrients should be conducted since deficiencies of most soil-derived essential nutrients (except Cl and Mo) have been reported in the grassland regions of North America (Bauer *et al.* 1978).

Nitrogen deficiencies are most common on abandoned mine sites. Nitrogen inputs to the system are required periodically until the N cycle is restored, which can take many years. The most efficient method of providing N is through the use of N-fixers (Skeffington and Bradshaw 1980, Jefferies *et al.* 1981, Palmer and Chadwick 1985). For example, Palmer and Iverson (1983) found the N input from white clover (*Trifolium repens*) on colliery spoil in England added up to 167 kg of N ha^{-1} yr^{-1} when sufficient P was available. The N fixed was supplied regularly throughout the growing season to associated grasses, whereas the spring-applied ammonium sulfate plots were deficient in N by summer's end (Palmer and Iverson 1985). Nitrogen input via actinomycetes (White and Williams 1985) and other N-fixing organisms is also encouraged.

The beneficial influence of mycorrhizal fungi in grassland rehabilitation should be emphasized as they enhance nutrient (especially P), and water uptake (which is notoriously poor in those environments) (Danielson *et al.* 1979, Allen and Allen 1980, Grossnickle 1985, Zak 1985). In fact, it has been shown that most plants established on mine spoil are mycorrhizal; successful non- mycorrhizal species frequently possess a weedy growth habit or ruderal strategy (Miller 1979). Mycorrhizae should be considered a necessary component of an overall rehabilitation strategy in order to obtain physical stability.

Alteration of pH. Since pH of the spoil material controls the availability of many essential and potentially toxic elements, regulation of spoil to circumneutral pH is highly desirable. Liming is widely used to raise the pH in acid spoil (Bradshaw and Chadwick 1980). In many cases pyrite oxidation continues to produce acid, and additional lime must be applied (Bloomfield *et al.* 1982). Care must be taken to incorporate the lime deeply; roots will not penetrate beneath that zone in highly acidic spoils (Fitter and Bradshaw 1974). It is also possible to apply too much lime to an area which results in temporary P deficiencies (Costigan *et al.* 1982).

In western grassland regions, mine spoils are alkaline rather than acidic in nature.

This is not a serious problem unless the pH is higher than 8. In such cases, S or sulfuric acid has been used, though with limited success, to reduce pH (Bauer *et al.* 1978); in most cases the pH will eventually drop.

Salt management. Excessive salt content, especially Na, is a major problem in abandoned mine areas and in areas contaminated by oil brine in the grassland regions of North America. Since precipitation infiltration amounts are often insufficient for adequate salt leaching on the affected areas, the problem continues. Any process designed to increase infiltration, such as mulching and grading, will hasten salt leaching. Incorporation of gypsum is also beneficial (Richards *et al.* 1954).

Plant selection. Considerable effort has been expended in finding plant species tolerant of the harsh conditions in abandoned mine spoils. Probably the best known example of this is the propagation of the metal-tolerant cultivar of *Agrostis tenuis* by Bradshaw and his coworkers (Cook 1981). Screening and breeding plants for adaptability to harsh environments has been important and will become even more important to reclamation practitioners (Asay 1979, Safaya 1979). Finding or producing varieties tolerant to drought, salt, nutrient deficiencies and/or toxicities will allow some abandoned areas to become vegetatively productive even if they have been bereft of vegetation for 40 years or more. Several sources are available to aid in the selection of plants for rehabilitating grasslands (Monsen and Plummer 1978, Fulbright *et al.* 1982, Redente *et al.* 1982, Thornberg 1982, Ries and DePuit 1984). It is also recommended that transplanted shrubs and grasses be considered for revegetating harsh sites (Cable 1977, Drake 1986). Several chenopod shrubs, including *Ceratoides lanata* and *Atriplex canescens*, can survive and grow well on harsh sites if they are transplanted in small tubes (Iverson 1986). Recently, Powell (1988) has synthesized an extensive list of plants and their major characteristics for rehabilitation of mined areas.

Legal Developments Regarding Mined Lands

Many state laws were developed in the late 1960s and 1970s to regulate the burgeoning areas of land left in devastated condition following coal mining. These efforts culminated nationally in 1977 with the passage of the federal Surface Mining Control and Reclamation Act of 1977. Since this is considered elsewhere in this book (Safaya and Wali 1991), only those aspects that are relevant to grassland rehabilitation are discussed here. Information on the Act (United States Congress 1977: 30 United States Code, paragraphs 1201-1328) comes primarily from Imes and Wali (1977, 1978) and Binder (1979).

The 1977 Act delegates primary enforcement powers to the states as long as they meet minimum federal standards. In many cases, present state requirements are more stringent than the federal minimum standards. The key element in the Act is the requirement for an approved permit prior to mining. This permit application must include a reclamation plan which includes the existing condition of the land, its uses and capabilities, proposed post-mining land uses, detailed techniques to be used to achieve that goal without infringing on current land use plans, air and water health/safety standards, and existing water systems and rights.

Minimum reclamation performance standards critical to rehabilitation efforts include maximizing utilization and conservation of coal, reclaiming land to previous or 'higher' uses, restoring original contours, backfilling, stratifying and replacing topsoil, stabilizing waste piles, minimizing disturbance to the prevailing hydrologic balance, preventing acid-mine drainage, minimizing suspended solids, restoring recharge capacity, preserving hydrologic functions of alluvial valley floors, preventing landslides and debris fires, and regulating road construction and maintenance.

The Act requires that land disturbed by surface coal mining be restored to its prior condition according to selected vegetational attributes. The U.S. Congress (1977) requires the operator to:

'Establish on the regraded areas, and all other lands affected, a diverse, effective, and permanent vegetative cover of the same seasonal variety native to the area of land to be affected and capable of self-regeneration and plant succession at least equal in extent of cover to the natural vegetation of the area; except, that introduced species may be used in the revegetation process where desirable and necessary to achieve the approved post-mining land use plan. . . .'

The final rules and regulations on the Act were issued six years later (United States Department of the Interior 1983b). This rulemaking outlines the permanent performance standards; selected parts pertaining to revegetation are cited here:

§816.111 revegetation: general requirements

(a) The permittee shall establish on regraded areas and on all other disturbed areas except water areas and surface areas of roads that are approved as part of the postmining land use, a vegetative cover that is in accordance with the approved permit and reclamation plan and that is –

(1) Diverse, effective and permanent;

(2) Comprised of species native to the area, or of introduced species where desirable and necessary to achieve the approved postmining land use and approved by the regulatory authority:

(3) At least equal in extent of cover to the natural vegetation of the area; and

(4) Capable of stabilizing the soil surface from erosion.

(b) The reestablished plant species shall –

(1) Be compatible with the approved postmining land use;

(2) Have the same seasonal characteristics of growth as the original vegetation;

(3) Be capable of self regeneration and plant succession;

(4) Be compatible with the plant and animal species of the area; and

(5) Meet the requirements of applicable State and Federal seed, poisonous and noxious plant, and introduced species laws or regulations. . . .'

In general, the land is to be returned to approximately the same use and capabilities as before mining. For most of the grassland region (where the average annual precipitation is less than 660 mm), a 10-year performance period is required to demonstrate revegetation success. Additional restructuring applies to farmlands: productivity following mining must be equal or better than before mining. For native grassland areas, cover, diversity as well as productivity should be restored.

Rehabilitation of Areas Mined Under Reclamation Laws

Common rehabilitation practices

According to the 1977 Act, regrading the land to its approximate pre-existing contour (with the exception of terrains such as those found in West Virginia), segregation and stratification of topsoil and subsoil to depth of 1.5 m, and burial of toxic or potentially toxic spoil must be accomplished. With rare exceptions, these practices are adhered to by active coal mining companies. The Act also states that the vegetation should be diverse and permanent and that equal productivity or better should be obtained over a 10-year period in the western United States.

The most common reclamation practices include regrading, replacement of topsoil, fertilization, and seeding with a native plant species mix. In most cases, the procedure works as follows: remove existing vegetation, remove and stockpile topsoil, remove and stockpile subsoil (up to a depth of 1.5 m), move overburden to other side of pit using a dragline, remove coal with shovel and truck, level overburden spoil piles with bulldozer, replace subsoil and topsoil using earth mover, carry out farming operations by applying fertilizer, prepare a seed bed, sow grass and forb seeds, and cover the area with mulch if needed.

Of course, variation from these procedures is extensive such that few mines use exactly the same procedures. All, however, are carefully monitored by state and federal regulatory personnel. A large number of guides have been published which help the operator obtain the goals approved in the reclamation plan. Those interested are encouraged to study these manuals to get an idea of all the variations (Moore and Mills 1977, Institute for Land Rehabilitation 1978, Samuel *et al.* 1979, United States Department of Agriculture 1979b-e, 1982, Barr Engineering and Borovsky 1980, Herricks *et al.* 1980, 1982, Leedy 1981, Leedy and Franklin 1981, Vogel 1981, Albrechtsen and Farmer 1987). Many of the guides also focus on variations used for the creation of fish and wildlife habitats.

Patterns of revegetation following reclamation

Given the above practices, the patterns of revegetation differ significantly from those of natural revegetation following abandonment. The site retains OM and a portion of microbial populations and propagules with the replaced topsoil. Initially, site fertility is greater than that on unmined sites because of the addition of fertilizers. The sites have an ample supply of potential seedlings with the reseeding operation, erosion is reduced by regrading and possibly mulching, pH is altered, and toxic (including sodic) materials are buried beneath the root zone. Because of these differences, vegetation development is, for the most part, hastened and is similar to secondary succession rather than the primary succession on AMLs.

Iverson and Wali (1982a) conducted a detailed investigation of patterns of revegetation during the first 4 years following regrading and replacement of topsoil. They compared these with an adjacent unmined site in western North Dakota. They documented the profound effect of pioneering species, especially *Kochia scoparia* (Chenopodiaceae), on the first year's growth, even though the area was seeded with a mix of native grasses. Of the 95 species recorded on all sites, *Kochia* was dominant in the first 2 years after mining; it had relatively low densities in the first year (50 to

80 plants m^{-2}), but it was robust and attained heights of 88 cm, with a biomass of 400 g m^{-2}. In the second year, *Kochia* densities increased to over 10,000 m^2, but height and biomass fell to 15 cm and 90 g m^{-2}, respectively. During the third and fourth years, *Kochia* was nearly eliminated, while the planted grass species (mostly *Agropyron* spp.) increased dramatically. Interspecific competition studies indicated that *Kochia* acted as a 'nurse crop' for several months during the first year of grass establishment; by July the canopy effectively closed, reducing light to the grass seedlings and decreasing rates of tillering. The rapid decline of *Kochia* was attributed to several factors, including intraspecific competition among second-year seedlings, interspecific competition with grasses, and autotoxicity in which decaying *Kochia* leaves and roots were found to retard the growth of *Kochia* but not of grasses. Species turnover during the first 4 years was dramatic, with increased richness each year. After 4 years, the plant composition bore little resemblance to the mined site.

Iverson and Wali (1982a) examined temporal trends in soil characteristics relative to adjacent unmined lands. At least 25 of 36 soil properties showed significant differences among sites of different ages. Electrical conductivity and the concentrations of water-soluble Ca, Mg, Na, Li, Sr, and SO_4 decreased with time due to leaching, while total N and organic matter increased. Some of these results are tabulated with the North Dakota AML study for comparisons of soil development under natural revegetation conditions (Table 5). Leaching of water-soluble salts (EC, Ca, Mg, SO_4), over 4 years on reclaimed sites was equivalent to 17 to 30 years of leaching on the upper slopes and less vegetated abandoned mines (Table 5). Initially, organic matter is higher on reclaimed sites and continues to build up with abundant litter production in the early years. The 45-year old abandoned sites, on the other hand, had only one-half the organic matter of the unmined area. A similar trend is apparent for total N; the reclaimed site began with more than twice the amount on the abandoned site. For P, the critical fertilization upon seeding caused P-levels to be greater than unmined areas, and much greater than abandoned areas. The pH showed no distinct trends in either case; clay content decreased in the upper surface zone with time. In both cases, the number of species generally increased with time. The comparison of total numbers of species is not valid because different methods (total area samples and time of sampling) were used.

Parmenter *et al.* (1985) also studied newly reclaimed mines in western Wyoming for their potential as wildlife habitats. Over a 7-year period, they found vegetation patterns similar to those identified by Iverson and Wali (1982a). Pioneer species were important during the initial successional period, and wildlife habitat quality increased rapidly with time as diversity was enhanced.

Problems in Rehabilitation of Reclaimed Areas

Many of the problems discussed for AMLs also pertain to reclaimed lands; however, problems with the latter are often less intense and dealt with more easily. For example, water deficits are still the main problem for most revegetating grasslands in the West, but the regraded nature of the area, the enhanced organic matter content and water-holding capacity of replaced topsoil, and the capacity to manipulate the surface and topography to maximize water conservation allow much better potential for adequate water supplies relative to AML sites. Burial of pyrite or sodic overburdens well below the rooting zone helps as well. Nutrient deficits can be corrected through fertilization. Still, problems exist, some because of ecological complexity, and others as a result of current reclamation practices.

Compaction

Depending upon the moisture conditions during the operation, the heavy earth-moving equipment typically used in mining operations to regrade overburden, respread subsoil, and replace topsoil, compacts the soil considerably. This can cause restrictions to root penetration and water infiltration, and thus reduce the potential of the site. This appears to be the most serious problem in reclaiming many mid-western soils to prime farmland production (Jansen 1981).

Long-term productivity and stability

Since SMCRA has been in effect for only one and a half decades, it is not yet clear whether long-term productivity and stability can be maintained on rehabilitated grasslands. Because of the current agricultural approach to active management, it is difficult to tell how the systems will behave when they are under extreme stress (Curry 1975).

Diversity

The Act also states that the reclaimed grassland species composition should be diverse. To date, no studies have revealed species diversity or richness on mined lands to even approach that of adjacent unmined sites. Many reasons have been put forth for maintaining and increasing biological diversity (Lieberman 1975, Wilson 1988), yet critical habitats are continuously being eroded by mining and other 'developments'. Killingbeck and Crompton (1979) suggested methods for safeguarding some of these critical habitats, physically moving threatened plants away from the mining area. Still, if diversity could be restored, the loss of critical habitats could be reversed.

Wildlife and woody species

We must also address the reduced quantity and quality of diverse habitats essential for wildlife following mining. Pursell (1983) noted that by reclaiming 'to equal or higher use' (cropland normally being considered a higher use than wildlife habitat or trees), forest and wildlife land uses suffer. Because no agency controls the land use following bond release, additional acreages are being converted to cropland.

Methods Used to Minimize Reclamation Difficulties

Many remedies discussed under the AML section are also pertinent to current reclamation practices. For example, water harvesting and conservation practices are recommended for for dry regions (Verma and Thames 1978). The search has continued for plant species adapted to harsh conditions on mined lands (Asay 1979, Safaya 1979). Some other techniques are discussed here.

Compaction reduction and soil mixing

Several ripping devices have been used to break up the hardpan at the topsoil-subsoil interface. They disrupt the surface 50-100 cm such that roots and water are able to penetrate (Bradshaw and Chadwick 1980). This technique has been shown to be especially beneficial for growth of deep-rooting plants such as trees and corn.

Soil mixing or blending has also been investigated to improve the physical and nutritional status of reclaimed soils. For example, it has been shown that in several Illinois soils, the substitution of a clay-rich subsoil with deeper zone material improves the productivity of the site (Dancer and Jansen 1981, McSweeney *et al.* 1981). Besides 'diluting' the clay-rich subsoil with coarser materials, and removing the tendency for hardpan formation, this method capitalizes on the higher P and K levels in the deeper material (Dancer 1982).

Mowing and grazing

Mowing has been shown to hasten early succession after mining by removing the dominant 'weedy' pioneering species (Iverson and Wali 1987). They found that if the large annuals, especially *Kochia scoparia*, were mowed in July of the first year just prior to seedset, the density of *Kochia* was reduced to one-quarter of the unmowed controls, and that planted *Agropyron* spp. had a more than 8-fold increase in biomass production in the second year. DePuit (1983) noted the benefits of grazing on mined land during a 3-year study in Montana. Grazing increased OM, N, and cation exchange capacity (CEC), and lowered C/N ratios. Light grazing generally improves the species density and soils (Hoffman *et al.* 1978).

Improved diversity

Many sources are available for selecting plant materials suitable for mined-land habitats (Monsen 1955, Grandt and Lang 1958, Chronis 1977, Hassell 1977, Nord 1977, Plummer 1977, Vories and Sims 1977, Bennett *et al.* 1978, Aldon and Pose 1981, Redente *et al.* 1982, Thornburg 1982, Ries and DePuit 1984). However, problems still exist in establishing a diverse community from multi-species plantings. Research is now underway to enrich diversity by transplanting or seeding shrubs (Luke and Monsen 1986), by altering the planting dates and water regimes during the initial establishment period (Ries *et al.* 1979), or by modifying planting techniques. Long (1985), for example, found that double-drilling is helpful in establishing warm-season grasses, forbs, and shrubs; the cool-season grasses, which are relatively easy to establish, were benefitted as well. Respreading the upper 5 cm of topsoil from unmined sites immediately on mined sites, rather than storing the topsoil at the bottom of a stockpile for 1 to 2 years, also enhances diversity by taking advantage of the seeds and propagules present in the unmined soil (Iverson and Wali 1982b).

Improving productivity

This aspect is being studied especially in the context of restoring prime farmland. Several soil reconstruction designs and fertility regimes are being investigated

(McSweeney *et al.* 1987). In some cases, Illinois crop productivity of mined lands has been enhanced above that of claypan unmined soils during dry years.

In grasslands, there is some indication of an inverse relationship between species diversity and biomass production (Biondini and Redente 1986). Both may not be attained simultaneously. If high diversity is a desired objective, the amount of fertilizer should be reduced. We need to know more about how to rationally manage restored landscapes so that we can strike the desired balance between biomass productivity and ecosystem resource use (Mooney and Gulman 1983). A fine discourse on productivity of rangelands in relation to plant materials selection, short- and long-term productivity and ecological principles is given in DePuit (1988).

Providing landscape perspective

As one views the mined-unmined landscape as an intertwined mosaic, additional ecological insights emerge (Risser *et al.* 1984, Risser 1991). Essentially, we are just beginning to learn how disturbance affects trends in functional landscape characteristics and landscape types (Godron and Forman 1983). The tools have been rapidly evolving and these relationships can now be addressed. For example, Brigham *et al.* (1987) used a geographic information system (GIS) and a remote sensing technology to assess recovery of abandoned mines in Illinois, and modeled the erosion problems during mining activities. Mausel *et al.* (1981) and Carrel (1984) also used remote sensing techniques to assess AML natural succession in Indiana and Missouri, respectively. Game *et al.* (1982) studied patch size, slope, and density during succession of mines in Missouri.

Although they did not use GIS techniques, Packer and coworkers (Packer 1974, Packer *et al.* 1979) modeled rehabilitation potentials over very large landscapes in the West. Such an approach can be used on finer scales to aid in reclamation efforts. Other computer programs assist in developing reclamation plans for mining operations, such as the CLAIM program (Scott 1979).

Comparison of Pre- and Post-reclamation Grassland Succession

With the discussion and data provided in this chapter, it is now appropriate to attempt a synthetic view of grassland ecosystem succession as it occurs on pre- and post-reclamation sites. It is not unlike making comparisons between primary and secondary succession, but it differs in that reclaimed sites have had substantial energy inputs into the system. Most of the trends presented are logically deduced from and substantiated by data such as that found in Table 5 (Iverson and Wali 1982a, Wali and Pemble 1982). We illustrate trends (Figs. 8-10) that principally apply to mixed grassland rehabilitation in the semiarid West, though most should be generally applicable to other grassland types. The AML temporal scales will obviously vary depending upon the ability of the spoil to support vegetation. The figures presented here are based on fairly hospitable material. Three categories of parameters were addressed: soil, vegetation, and ecosystem. Our 'trend' lines in Figs. 8-10 have a 50-year time line for pre-legislation sites, and a 10-year time line for post-legislation sites.

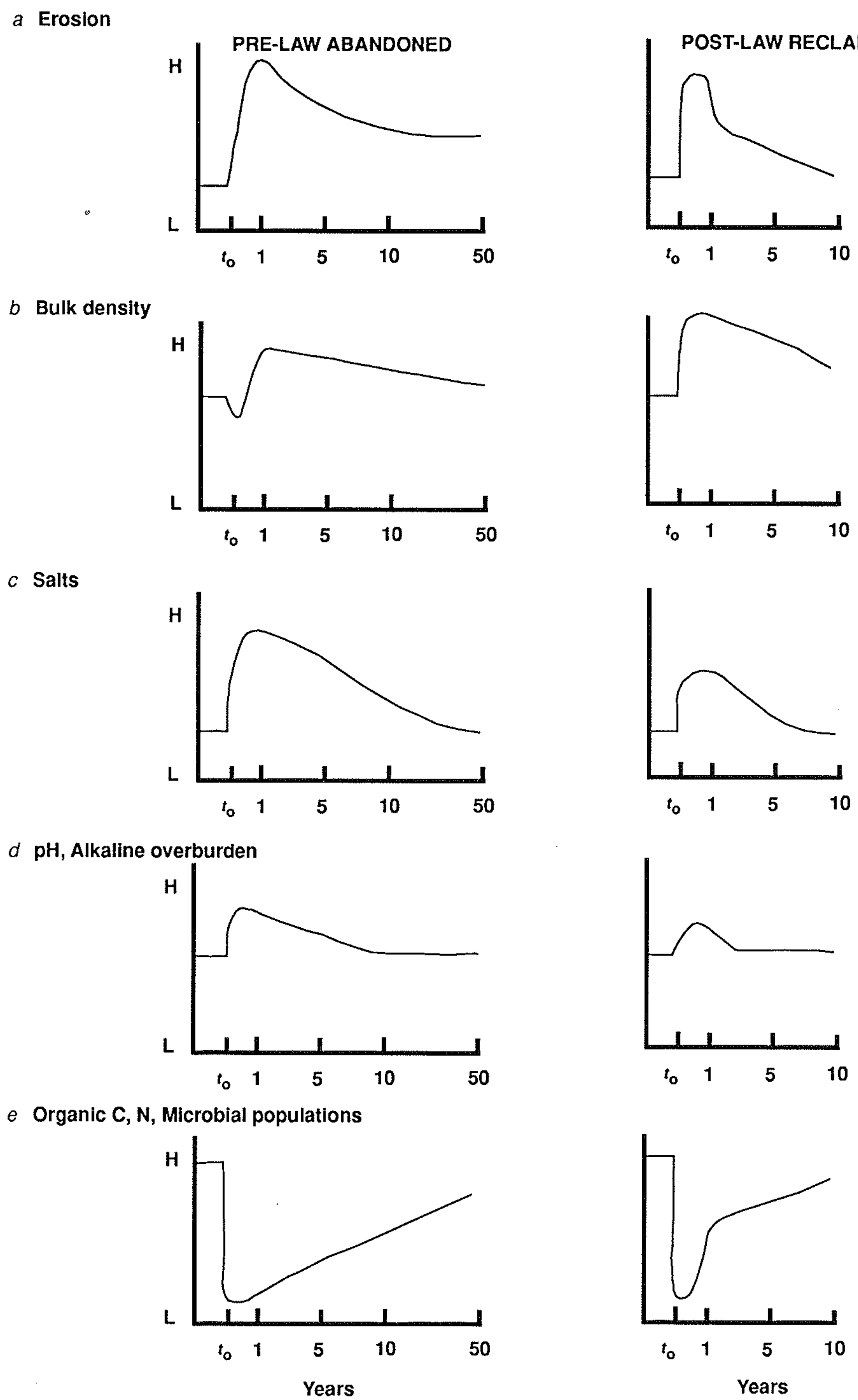

Fig. 8. Temporal trends in spoil and soil properties. High (H) and low (L) lines denoted to the left of t_0 approximate pre-mining conditions.

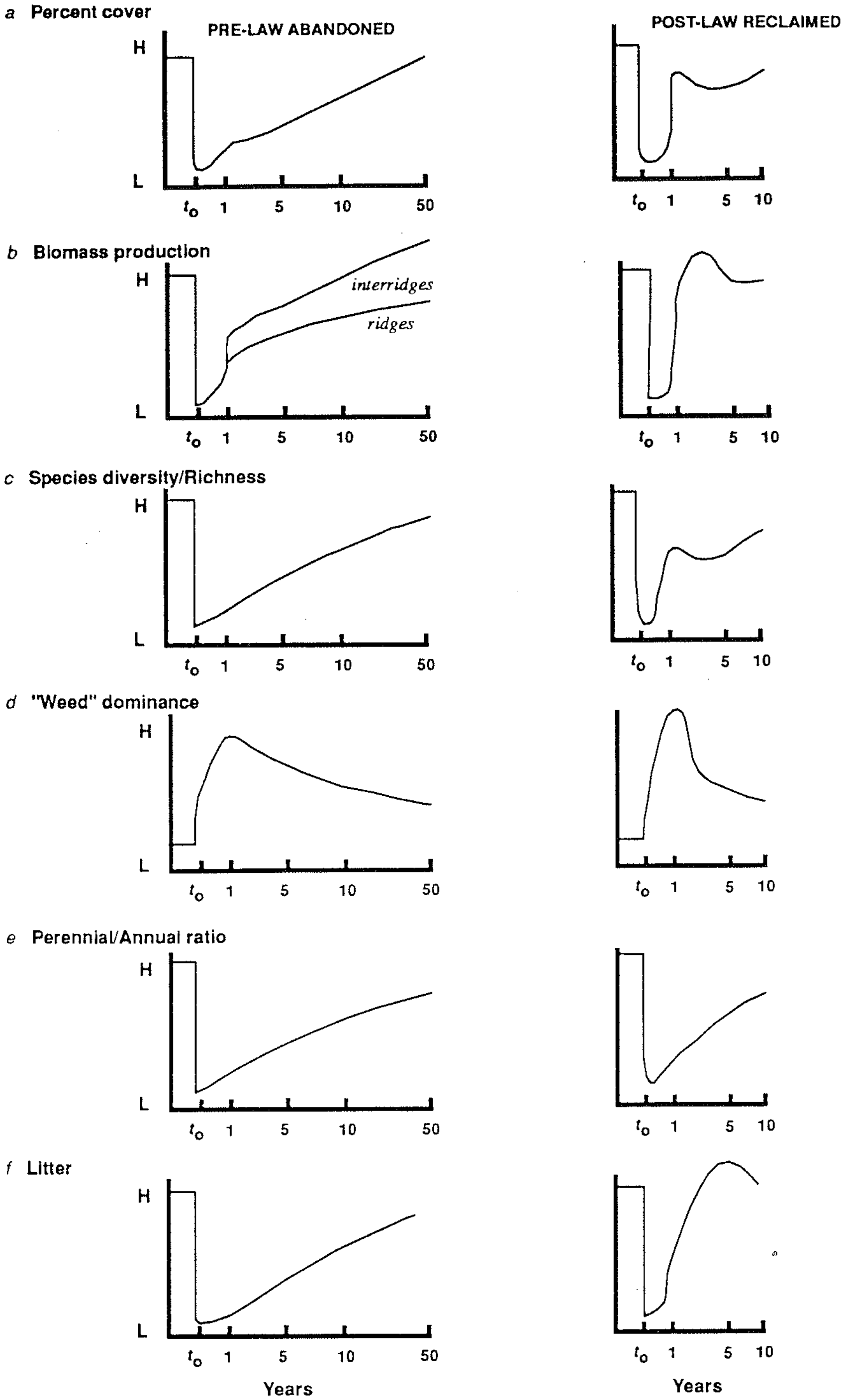

Fig. 9. Temporal trends in vegetation characteristics. High (H) and low (L) lines denoted to the left of t_0 approximate pre-mining conditions.

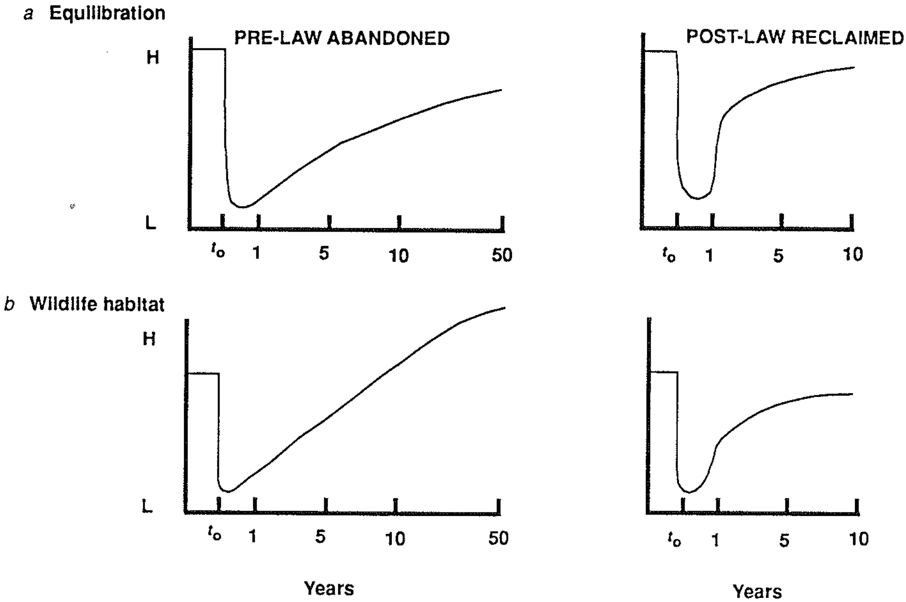

Fig. 10. Temporal trends in (a) ecosystem equilibration, and (b) ecosystem use as wildlife habitats. High (H) and low (L) lines denoted to the left of t_0 approximate pre-mining conditions.

Soil and spoil characteristics

Soil erosion is obviously greatly exacerbated by mining disturbance since all vegetative cover is removed (Fig. 8a). AML sites never fully recover to pre-mining levels of higher slopes and reduced cover. Reclaimed sites generally return to the pre-mined state after 3 to 4 years of vegetation establishment. Soil bulk density shows a short-time decrease on AML sites immediately after mining as material is piled up by the dragline, but quickly increases above pre-mining levels because of the non-friable nature of the spoil (Fig. 8b). Then, it slowly decreases with time as vegetation and soil organisms grow. The reclaimed site, on the other hand, generally shows a large increase in bulk density as a result of traffic from earth-moving equipment. It will decrease rapidly assuming good vegetative growth so that the rooting-zone bulk density should approximate that of unmined areas after 10 years.

Water-soluble salts tend to decrease rapidly with time in both systems, though much faster in reclaimed sites (Fig. 8c). In the North Dakota studies, EC leveled to pre-mined conditions after an estimated 10 to 15 years (Table 5). It should be noted, however, that vegetation establishment at the AML sites described above was not hampered by sodicity. The sites with sodicity problems develop at a much slower rate because excessive Na disperses soil colloids and reduces percolation. The pH of alkaline spoil does not change rapidly, but is expected to decrease slightly with time after an initial rise in pH following mining (Fig. 8d). Organic C and N levels, as well as soil microbial populations, are destroyed by the mining process; they build-up very slowly on AML sites, and are restored to approximately 50 to 70 percent of the original level on reclaimed sites following the replacement of stockpiled topsoil (Fig. 8e). Using simulation models, Anderson (1977) and Wali and Pemble (1982) estimated that it would be over 200 years before pre-mining levels of N would be attained on their respective AML sites.

Vegetative characteristics

These characteristics are intimately tied to the nature of the material upon which they grow. As such, the temporal scales presented in Fig. 9 would fluctuate accordingly; the generalized presentation is based on non-sodic, non-acidic spoil material. Percent cover shows a gradual increase with time to approximately pre-mining conditions after 20 to 30 years (Fig. 9a). Vegetative cover on reclaimed sites is almost 100 percent in the first year due to pioneer growth, but is reduced somewhat in the second and third years; the planted grasses attain full stature in the fourth year. Biomass production follows a pattern of gradual increase following mining on AML sites, and it may even exceed pre-mining levels in the interridge zones where moisture collects after 20 to 30 years; however, the steeper slopes would not be expected to ever attain full growth potential (Fig. 9b). Reclaimed sites rapidly increase in biomass, although in the first 2 years most of the biomass is from weedy annuals. Planted cool-season grasses may also attain greater productivity than the unmined sites because of their capacity to capitalize on winter precipitation and because reclaimed sites are fertilized. After 5 to 10 years, however, cool-season grasses decrease in importance, fertility is reduced, and biomass productivity stabilizes at roughly the pre-mining level.

Species richness or diversity is expected to increase slowly on AML sites, and will reach 50 to 60 percent of the pre-mined level at 50 years (Fig. 9c). On reclaimed sites, richness increases rapidly over the first 2 years because of annual colonizers and planted species. It then dips somewhat because of the decline in annual grasses and finally increases steadily. Weed dominance shows a very rapid rise following mining in both situations, with a rapid decline after 2 years on reclaimed areas following the rise of planted grasses (Fig. 9d). On AML sites, weed dominance decreases more slowly due to the lack of seed supply from competing perennials, and because the sites maintain a sparse cover allowing annuals to become established. Related to weed dominance is the perennial-to-annual ratio, which slowly increases after mining but has a steeper slope on reclaimed sites (Fig. 9e).

Litter drops to zero following mining, and it slowly increases thereafter on AML sites (Fig. 9f). On reclaimed sites, the extra biomass from cool-season grass growth in the third to sixth years causes a rapid build-up of the litter layer such that it exceeds that of unmined areas. This indicates the importance of fire, grazing, or haying on mined lands during this phase of growth when fertility and productivity are high.

Ecosystem characters

The stability of the system and the ability of the system to tolerate perturbations or environmental extremes without collapse (equilibration), increases following mining in both situations, but at a faster rate on reclaimed lands (Fig. 10a). Wildlife habitat is very poor during initial establishment years in both situations. If one considers the entire mined AML area, the wildlife potential could increase above that of pre-mining conditions, because the presence of ponds and interridge zones may add habitat diversity Fig. 10b). This would be especially true if trees were planted in some of the interridge zones, or if a wind-dispersed species like cottonwood (*Populus* *deltoides*) were present on adjacent areas. With the establishment of a few trees, bird-dispersed trees and shrubs would likely follow.

Research Needs for Grassland Rehabilitation

The following items appear to be the most important research needs for grassland rehabilitation in North America, and are listed according to soil and spoil, vegetation, and ecosystem and landscape functions.

Soil and spoil

· Prevent or ameliorate compaction. Mining procedures can be altered to prevent problems such as compaction. Bucket-wheel excavators and judicious truck-hauling of topsoil can reduce traffic on the topsoil. Additional work needs to be conducted on utilizing these methods on an economic basis.
· Reassess adequacy of critical limits for spoil, soil, and water. It is not clear what the tolerable limits are for plant growth, and what the critical limits should be for materials requiring special handling.
· Uncover the nature and mechanisms for movement of salt, acidity, and water. The lateral and vertical movement of salt, acidity, and water through disturbed soils is poorly understood, and it needs clarification to enable proper handling of materials. There is risk of developing new salinity or acidity problems after several years of 'successful' rehabilitation.
· Determine methods of and basis for reintroduction of soil organisms. The importance of soil organisms in overall ecosystem health has been established. Are there ways in which microbial succession can be hastened and insure, for example, that the proper species of mycorrhizae, *Rhizobium* and *Frankia*, are available?
· Monitor soil development and rates of change. The mined land ecosystem offers us a great deal to learn about ecosystem development. As such, studies that assess changes in ecosystem development over time should be continued.
· Identify the best methods for moisture harvesting and conservation. Water remains the most serious limiting factor in the rehabilitation of western North America grasslands. Any methods that can be devised which conserve moisture and retard erosion will be highly beneficial.

Vegetation

· Determine the cultural practices that increase survival and growth of multispecies plantings, including tree and shrub components. Increasing diversity in a timely fashion is needed for enhancement of ecosystem stability and wildlife habitat.
· Monitor succession, long-term productivity, and rates of change. Additional research is needed on a long-term basis to better understand the rates of vegetation change under various management and initial planting conditions.
· Conduct ecotype and genotype studies to find plants adapted to various stresses. Breeding and screening studies should be continued to find species or cultivars suited for growth under extreme stress due to salinity, sodicity, acidity, and nutrient or moisture deficiency.

• Understand ways in which pioneer species contribute to site reclamation. Additional effort should be made on ways to utilize colonizing vegetation to advantage in reclamation. For example, the colonizers could be considered 'nurse crops' until the point after which they become excessively competitive. Mowing at the correct time may allow the beneficial effects to be maximized and the detrimental effects to be minimized.
• Determine the role of pathogens and insects in the rehabilitation process. Virtually no work has been done in this field. Iverson and Wali (1982a) observed heavy cocklebur weevil larvae infestations on pioneer species. Are pioneer species more susceptible to such invasions? Do pathogenic fungi play a role in successional processes?

Ecosystem landscape

• Reduce the traditional agricultural approach to management. High levels of fertilizer may be detrimental in obtaining high species diversity. Other human inputs may also be detrimental to the system. Research is needed on how to balance establishment success with adequate species diversity.
• Incorporate the capacity to accommodate extremes in stress factors. With regard to the reduction of the agricultural approach to management, this point emphasizes the importance of homeostasis in ecosystems, the resiliency to bounce back after one extremely dry year, or after a serious disease or insect outbreak.
• Determine the role of landscape heterogeneity in desired final site conditions. The movement of energy and materials among the components of a mining landscape is extremely important in determining the characteristics of the overall landscape. Recruitment of species onto rehabilitation areas is critically important in achieving rehabilitation success. Similarly, movement of soil, contaminated water, or enriched water from 'leaky' disturbed systems can be of great importance in the overall health and vigor of the surrounding unmined landscape.
• Make use of remote sensing and geographic information systems to spatially address reclamation potential and success. The tools are in place to greatly aid in predicting, tracking, and managing the rehabilitation process. The regulatory authorities and mining companies would especially benefit from the technologies, but they would also allow for easier spatial and temporal comparisons of rehabilitation success. In turn, it would allow for growth of the knowledge data base on what methods were successful under various conditions.
• Develop models that predict reclamation success under various treatment options. This effort could be facilitated by the GIS technologies previously discussed. Tying simulation models to the ground through a GIS allows specificity in handling materials to maximize effectiveness and minimize costs.
• Investigate wildlife introduction and productivity on reclaimed grasslands. Innovative ideas are needed to encourage wildlife populations to reinhabit disturbed systems. Numerous guides are available on the subject, but more effort is needed to increase wildlife use.
• Reassess methods for evaluating success of reclamation. Regulatory authorities are charged with assessing reclamation success, and thereby control the release of bond monies posted by the mining companies prior to mining. It is not easy, and sometimes not relevant, to compare growth on the mined areas with unmined reference areas.

They are very different ecosystems. Would it be possible to use some combination of soil characters in evaluating rehabilitation success?

Postscript

We have learned much in the past decades from intensive studies on ecosystem rehabilitation in arid and semiarid regions in the United States and Canada. Although we have concentrated here on ecological aspects only, studies are available on social and economic aspects as well. Many of these studies, with modifications, can be used directly in other such regions of the world. The disturbance brought about by mining and other activities can be transformed into an opportunity if we accept the challenge to create landscapes that are beneficial to society. Simultaneously, we will learn much more about many fundamental ecological processes as well.

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