Evaluating the Ecological Sustainability of a Pinyon-Juniper Grassland Ecosystem in Northern Arizona

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Abstract—In order to develop strategic land management plans, managers must assess current and future ecological conditions. Climate change has expanded the need to assess the sustainability of ecosystems and predict their conditions under different climate change and management scenarios using landscape dynamics simulation models. We present a methodology for developing a state-and-transition model (STM) with the Vegetation Dynamics Development Tool (VDDT), using outputs from the Forest Vegetation Simulator (FVS). Preside, a recently developed accessory to the FVS program, is used to process and report FVS outputs in terms of succession probabilities and residence times for each STM. We've applied these tools with a case study based on the pinyon-juniper grassland ecosystem in northern Arizona. After applying local probability values for natural growth, contemporary fire, insect and disease, and management activities, VDDT simulations were conducted to project future ecosystem conditions including carbon accounting. Finally, we also describe how these models can be retooled with FVS support to reflect the effects of climate change so that managers can consider adaptation and mitigation strategies.

Introduction

The objective of this paper is to illustrate through a case study how State-and-Transition Models (STMs) can be developed and used to evaluate the ecological sustainability of ecosystems.

Projecting transitions in vegetation states (composition and structure) over time facilitates evaluating the ecological sustainability of ecosystems. Vegetation states can change in "the absence of disturbance" through natural regeneration, growth, competition and mortality; change also can result from disturbances and other discrete events in time such as fire, management activity, insect and disease outbreaks, etc. To facilitate projecting the effects of the interactions of these agents of change, landscape STMs such as the Vegetation Dynamics Development Tool (VDDT) developed by ESSA Technologies Limited (2006) can be used to quantify the dynamics of vegetation change (He 2008).

Ecological sustainability analysis evaluates both ecosystems (*ecosystem diversity*) and their associated species (*species diversity*). A guiding principle for ecosystem management (FEMAT 1993) is to use ecosystem reference conditions, the range of variation, as an inference of ecological sustainability to enable the persistence of ecosystem function and species diversity. In this paper, we focus on vegetation diversity and related ecological processes such as fire, and apply a case study assessing the ecological sustainability of the *pinyon-juniper grassland* ecosystem on the Coconino National Forest (NF) in northern Arizona.

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Methods

Framing the Analysis

We stratified the Coconino NF by potential natural vegetation types (PNVTs) (Schussman and Smith 2006), a coarse ecosystem framework defined by site potential and historic fire regimes, that provides a basic framework for analyzing ecosystem diversity. Although the same process was used on each PNVT, this paper documents the analysis process conducted on the 122,086 hectare (301,675 acres) pinyon-juniper grassland PNVT.

The pinyon-juniper grassland type occurs across the States of Arizona and New Mexico, in what was historically open woodlands with grassy understories (Ffolliott and Gottfried 2002). On the Coconino NF tree species include twoneedle pinyon (*Pinus edulis* Engelm.), oneseed juniper (*Juniperus monosperma* (Engelm.) Sarg.), Utah juniper (*Juniperus osteosperma* (Torr.) Little), and alligator juniper (*Juniperus deppeana* Steud.). On reference sites, native understories are made up of predominantly cool season perennial grasses including muttongrass (*Poa fendleriana* (Steud.) Vasey), squirreltail (*Elymus elymoides* (Raf.) Swezey ssp. *brevifolius* (J.G. Sm.) Barkworth) and western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve), with both annual and perennial forbs, while shrubs are absent or scarce (<1 percent cover)(Miller and others 1995). Contemporary understories often include invasive grasses such as cheatgrass (*Bromus tectorum* L.) and a dominance of warm season species such as blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths), and have uncharacteristically high shrub cover. This pinyon-juniper woodland type is typically found on sites with well-developed and moderately deep soils with loam and clay loam surface textures. Soil orders include mollisols derived from basaltic parent materials, andisols formed from cinder deposits and alfisols developed from sedimentary sources. Climate is characterized by a seasonal distribution of precipitation of which over half occurs between the months of April through September, with an annual rainfall ranging from 15-18 inches.

Information on the historic condition of this type is sparse. The ability to reconstruct historic stand structure and fire chronologies in pinyon-juniper is problematic, so the role of fire and the resulting vegetation structure is often speculative (Jacobs 2008). However, site productivity suggests that the development of a grass and fine fuels layer would have supported frequent fire, open forest dynamics, and perhaps uneven-aged conditions (Gottfried 2003).

We described historic (reference), current, and future structural conditions according to standard classification schemes based on average tree size (diameter) and canopy cover class (Brohman and Bryant 2005; table 1). Due to disparities in historic and current condition references, and how they were developed, it was necessary to develop crosswalks to normalize across references and enable comparisons between historic and current conditions. For instance, the U.S. Department of Agriculture (USDA), Forest Service mid-scale mapping, used to depict current conditions (Mellin and others 2008), uses a canopy cover break of 30 percent to distinguish open and closed, versus the LANDFIRE model (Havlina 2005) that employs a 40 percent break. We portrayed historic, current, and future *composition* conditions according to a southwestern regional classification of existing vegetation based on dominance types (Triepke and others 2005). Dominance types, defined by the relative abundance and dominance of tree species, are similar to Society of American Foresters or Society for Range Management cover types (Eyre 1980; Shiflet 1994), but are keyable, exhaustive, and mutually exclusive.

Table 1—Crosswalk to facilitate comparison of historic, current, and future conditions of the pinyon-juniper grassland ecosystem.

Reference Condition LANDFIRE RA JUPI1 Model			**Current Condition USDA FS R3 Mid-Scale EV Map**		**Future Trends USDA FS R3 PJ Grassland Model**	
State	**Mean[a]**	**Description**	**Dominance Unit**	**Structure[b]**	**State**	**Description**
A	5%	Post replacement	Non-tree: Recently burned and all shrub, grass, and forb types	Grass-forb-shrub	A	GFB/SHR
				Seed/sap-open	B	SSO
C	25%	Mid-open	—	Seed/sap-closed	E	SSC
			All pinyon, juniper, and mixed shade intolerant tree dominance types occurring within the pinyon-juniper grassland PNVT	Small-open	C	SMO
D	50%	Late-open		Med to very large-open	D	MVO
B	10%	Mid development closed		Small-closed	F	SMC
E	10%	Late-closed	—	Medium to very large-closed	G	MVC

[a] Average proportion of the landscape during the reference period (circa 880-1880 (Schussman and Smith 2006)).

[b] Size classes based on diameter at breast height for forest tree species and diameter at root collar for woodland species: seedling/sapling (< 13cm), small (13–24.9cm), medium (25–50cm), and very large (>50cm): overstory cover classes are sparse (<10% tree canopy cover), open (10 – 29.9% cover), and closed (>29.9% cover).

Specific combinations of dominance type, size class, and canopy cover that are characteristic to each PNVT are expressed in terms of *vegetation states* identified for each PNVT, and configured in PRESIDE (Process RESIDEnce Times), a recently developed ancillary program (Vandendriesche 2009) to the Forest Vegetation Simulator (FVS) model (Dixon 2002). Each vegetative state represents an important phase in the ecosystem dynamics of a PNVT. The historic pinyon-juniper grassland ecosystem has been described (LANDFIRE 2007) as a five-state model that includes a grass-forb state (A), two open forest states (C and D), and two closed forest states (B and E) (table 1). Frequent surface fires maintained the forest in these reference conditions. *Ecological process* reflects the ability of natural and anthropogenic events such as fire, forest insect and disease, and resource management activities to alter vegetation composition and structure and, in turn, wildlife habitat and species diversity (Perry and Amaranthus 1997). Along with site potential, the characteristic frequency and severity of fire are differentia of the PNVT classes themselves.

Describing Reference Conditions

The Vegetation Dynamic Development Tool (VDDT, ESSA 2006) has been used by the National LANDFIRE program (Ryan and others 2006) and others such as the Nature Conservancy (TNC) (Schussman and Smith 2006) to develop state-and-transition models that describe reference conditions. The VDDT software moves cells (representing a unit of area) from one state to another based on a set of "transitions." Traditionally, "deterministic transitions" describe succession (aging) in the absence of disturbance. Probabilistic transitions reflect the quantitative assessments of discrete natural and anthropogenic events including fire, insects, diseases, grazing, harvesting, and severe weather events. Each probabilistic transition typically has three characteristics that define its pathway: 1) its return frequency or probability, 2) its severity or impact on vegetation, and 3) the destination state in which the cell will reside after transition.

We retooled these models to project future conditions by replacing historic probabilities and transitions with contemporary transitions and attendant frequencies that reflect current land management. We also added contemporary and possible future vegetative states. We detail the development of the pinyon-juniper grassland model below. Reference condition descriptions and models typically are based on peer-reviewed journal articles as well as published conference proceedings, reports, theses, dissertations, and book chapters along with some consideration of professional judgment provided by model developers. In contrast, the models that we developed for projecting future conditions were more empirical, using Forest Inventory and Analysis (FIA) data, FVS simulation runs, and related software tools.

Describing Current Conditions

We mapped PNVTs using Terrestrial Ecosystem Survey (TES) data for the Coconino NF (Miller and others 1995). The TES is a terrestrial ecological unit inventory that formulates map units based on similarities in climate, soils, landform, and potential vegetation at the map scale of 1:24,000 (Winthers and others 2005). Among the map unit attributes, disclimax classes (zootic, fire) indicate historic disturbance regime, making TES map data the best available resource for PNVT mapping.

In 2004, the Southwestern Region initiated mid-scale mapping of existing vegetation at 1:100,000 across all National Forests and Grasslands (Mellin and others 2008). This mapping includes the three principle existing vegetation map components previously mentioned—dominance type, size class, canopy cover. With the description of vegetation states (table 1), these map data allowed for the quantitative analysis of current conditions within each PNVT. We intersected PNVT mapping in GIS with the existing dominance type, size class, and canopy cover layers from mid-scale vegetation mapping products to produce tabular summaries of current conditions within each PNVT class. These summaries were in turn synthesized to give hectares and percent of each vegetation state within each PNVT. We then compared these percents to historic and projected conditions for the ecosystem.

Along with each condition reported (historic, current, or projected), we calculated *ecosystem condition class* values using the same equation employed by LANDFIRE to compute Fire Regime Condition Class (FRCC) (Hann and others 2005). But unlike FRCC, which provides percentages for each departure class (1, 2, or 3), our own ecosystem condition class (ECC) provides one overall departure rating for a given analysis area (Weisz and others 2009). The ECC is computed for each comparison, either current vs. reference condition, or projected vs. reference condition (table 2) based on the departure of all states in total from their reference conditions. In each calculation, the sum of the lesser of percent values for each state, either reference or current, is subtracted from 100 to provide one overall departure index on a scale of 0 percent to 100 percent, higher values representing more departed conditions. From there, three classes make up the ECC rating system:

- ECC 1 (within reference condition) represents departure index values ≤ 33;
- ECC 2 (moderately departed) represents departure index values >33 and ≤ 66; and
- ECC 3 (severely departed) represents departure index values > 66.

Recently developed FRCC map data for LANDFIRE map zones in Arizona (LANDFIRE 2008) corroborate our findings, as do regional studies of these systems.

Table 2—Calculation of departure and ecosystem condition class based on the disparity between reference and current conditions for the PJ grassland ecosystem on the Coconino NF.

	Reference condition		Current condition	
State	Description	Mean[a]	Proportion	Calculation[b]
A	Post replacement	5%	23%	5%
C	Mid-open	25%	14%	14%
D	Late-open	50%	27%	27%
B	Mid development closed	10%	17%	10%
E	Late-closed	10%	19%	10%
			Sum	66%
			Departure index value = 100% - Sum	34
			Ecosystem condition class 1 (0–33), 2 (34–65), 3 (66+)	"2"

[a] Average proportion of the landscape during the reference period (circa 880-1880 (Schussman and Smith 2006)).

[b] Lesser of reference condition and current condition.

Projecting Future Conditions

Retooling models—Typically reference conditions models are based on a survey of the literature, supplemented by empirical data as well as expert opinion (LANDFIRE 2008). Often these models are applicable to a large map zone or to a large region like Arizona and New Mexico (Gori and Bate 2007; Havlina 2005). To retool these models to project conditions under existing or proposed management schemes, managers can modify reference condition models to: 1) include new states or modified states that reflect vegetation classes that did not exist under reference conditions; 2) incorporate current and projected natural and anthropogenic processes; and 3) incorporate current and projected transition probabilities. We illustrate by example how the Coconino NF retooled the pinyon-juniper grassland reference condition model for this purpose (see below), with the assumption of no climate change. Carbon accounting was also provided using the carbon extension of FVS (Havis and Crookston 2008; Hoover and Rebain 2008). The carbon extension provides values for dead and live standing trees, and dead and live belowground tree tissue (Hoover and Rebain 2008). Standard values are provided for carbon held in herbs and shrubs, downed wood, and litter and duff, based on similarly measured plant communities. The paper concludes with a description of how the model could be retooled in the future to consider climate change.

New or modified states—Typically, models for current and projected conditions contain as many or more states than reference condition models. In the case of the pinyon-juniper grassland PNVT, we developed a seven-state model to describe current conditions in contrast to the reference conditions model that had five states. Table 1 illustrates how we cross walked the reference conditions states with the current states.

Quantifying current transitions—To retool reference condition models to reflect contemporary processes, four steps are followed: 1) identify the contemporary transitions; 2) replace reference transitions with contemporary ones (tables 3, 4a and 4b); 3) model future conditions; and, 4) interpret the results. Each contemporary transition is identified in terms of its type, transition class (groups

Table 3—Canopy cover and fire mortality proportion table.

Canopy Cover / Fire Mortality Proportion Table		
Beginning Canopy Cover Class	Fire Severity Class	Ending Percentage by Canopy Cover Classes
10 – 30% (open)	non-lethal	9% → sparse (0 – 10%)
		91% → open (10 – 30%)
	mixed severity	55% → sparse (0 – 10%)
		45% → open (10 – 30%)
	stand replacement	100% → sparse (0 – 10%)
30 – 60% (closed)	non-lethal	16% → open (10 – 30%)
		84% → closed (30 – 60%)
	mixed severity	2% → sparse (0 – 10%)
		79% → open (10 – 30%)
		19% → closed (30 – 60%)
	stand replacement	87% → sparse (0 – 10%)
		13% → open (10 – 30%)

of transition types), frequency, and effects. We used four transition classes in our current model: wildland fire, management activities, insect and disease, and natural growth transitions in the absence of disturbance. Transition types within each transition class may have unique frequencies and effects unto themselves. The management activities transition class contains, for example, mechanical thinning, prescribed burning, etc.

Wildland fire transitions—We used LANDFIRE definitions of fire severity based on how much overstory canopy mortality would occur during a wildland fire: nonlethal (or low severity), <25 percent mortality; mixed severity fire, 25 percent to 75 percent mortality; and stand replacement fire, >75 percent mortality (Hann and others 2005). We generated fire frequencies for each of the transition classes using local fire history data on the planning unit for the period 1988 through 2006. Spatial data was available for approximately five wildland fires greater than 40 hectares (16 acres) in size for the period 1960 to 2005. Fire mortality mapping was available for three incidents including the Lizard (2003), Mormon (2003), and Jacket (2004) fires. For other fires that occurred after 1975, fire officials provided estimates of the percentage of non-lethal, mixed severity, and stand replacement fire that occurred. We corroborated fire mortality for the fires using orthophotos in GIS, estimating fire extent and mortality based on patterns of top-kill and regeneration.

We summarized these results as average annual probabilities per hectare for each fire type: nonlethal fire (0.0002), mixed severity fire (0.0021), and stand replacing fire (0.0032) and assigned these probabilities to each model state (table 4a). The mixed severity and stand replacement probabilities can be attributed to significant Pinyon Ips bark beetle activity since 1996. The effects of a fire on a cell within the model depend on pre-fire canopy cover and the severity of the fire (the fire mortality class; table 3).

Management activity transitions—We quantified management activities using the Forest Activity Tracking System (FACTS) database (M. Pitts, unpublished data). We queried all activities recorded on the planning unit from 1988 through 2006, and then eliminated activities that did not affect broad-scale vegetation

Table 4a—Pinyon-juniper grassland natural and anthropogenic disturbance transitions expressed as the average annual probability per hectare per year.

From State Code: Acronym: Description: Transition Type	Probability	Proportion[a]	To State Acronym
A: GFB: Grass/Forb/Brush			
Nonlethal Fire	0.0002	1.00	GFB
Stand Replacing Fire	0.0032	1.00	GFB
B: SSO: Seed/Sap, Open			
All Regeneration	0.0011	1.00	GFB
Insect and Disease	0.0100	1.00	SSO
Mixed Severity Fire	0.0021	0.55	GFB
Mixed Severity Fire	0.0021	0.45	SSO
Nonlethal Fire	0.0002	0.09	GFB
Nonlethal Fire	0.0002	0.91	SSO
Stand Replacing Fire	0.0032	1.00	GFB
C: SMO: Small, Open			
All Regeneration	0.0011	1.00	GFB
Insect and Disease	0.0100	1.00	SMO
Mixed Severity Fire	0.0021	0.55	GFB
Mixed Severity Fire	0.0021	0.45	SMO
Nonlethal Fire	0.0002	0.09	GFB
Nonlethal Fire	0.0002	0.91	SMO
Stand Replacing Fire	0.0032	1.00	GFB
D: MVO: Medium to Very Large Open			
All Regeneration	0.0011	1.00	GFB
Insect and Disease	0.0100	1.00	MVO
Mixed Severity Fire	0.0021	0.55	GFB
Mixed Severity Fire	0.0021	0.45	MVO
Nonlethal Fire	0.0002	0.09	GFB
Nonlethal Fire	0.0002	0.91	MVO
Stand Replacing Fire	0.0032	1.00	GFB
E: SSC: Seed/Sap Closed			
All Regeneration	0.0011	1.00	GFB
Insect and Disease	0.0100	1.00	SSO
Mixed Severity Fire	0.0021	0.02	GFB
Mixed Severity Fire	0.0021	0.19	SSC
Mixed Severity Fire	0.0021	0.79	SSO
Nonlethal Fire	0.0002	0.84	SSC
Nonlethal Fire	0.0002	0.16	SSO
Stand Replacing Fire	0.0032	0.87	GFB
Stand Replacing Fire	0.0032	0.13	SSO
F: SMC: Small, Closed			
All Regeneration	0.0011	1.00	GFB
Insect and Disease	0.0100	1.00	SMO
Mixed Severity Fire	0.0021	0.02	GFB
Mixed Severity Fire	0.0021	0.19	SMC
Mixed Severity Fire	0.0021	0.79	SMO
Nonlethal Fire	0.0002	0.84	SMC
Nonlethal Fire	0.0002	0.16	SMO
Stand Replacing Fire	0.0032	0.87	GFB
Stand Replacing Fire	0.0032	0.13	SMO
G: MVC: Medium to Very Large Closed			
All Regeneration	0.0011	1.00	GFB
Insect and Disease	0.0100	1.00	MVO
Mixed Severity Fire	0.0021	0.02	GFB
Mixed Severity Fire	0.0021	0.19	MVC
Mixed Severity Fire	0.0021	0.79	MVO
Nonlethal Fire	0.0002	0.84	MVC
Nonlethal Fire	0.0002	0.16	MVO
Stand Replacing Fire	0.0032	0.87	GFB
Stand Replacing Fire	0.0032	0.13	MVO

[a] Proportion of acres affected by a transition that will move to the destination state.

Table 4b—Pinyon-juniper grassland natural growth in the absence of disturbance successional transitions expressed as the average annual probability per hectare per year.

From State Code: Acronym: Description	Probability	To State Acronym
A: GFB: Grass/Forb/Brush	.9691	GFB
	.0136	SSO
	.0041	SMO
	.0132	MVO
B: SSO: Seed/Sap, Open	.9249	SSO
	.0269	SMO
	.0247	SSC
	.0236	SMC
C: SMO: Small, Open	.0045	SSO
	.9175	SMO
	.0193	MVO
	.0024	SSC
	.0494	SMC
	.0070	MVC
D: MVO: Medium to Very Large Open	.0078	SSO
	.0036	SMO
	.9714	MVO
	.0014	SSC
	.0016	SMC
	.0142	MVC
E: SSC: Seed/Sap Closed	.9093	SSC
	.0907	SMC
F: SMC: Small, Closed	.0004	SSC
	.9759	SMC
	.0237	MVC
G: MVC: Medium to Very Large Closed	.0003	MVO
	.0002	SSC
	.0036	SMC
	.9960	MVC

composition and structure from further analysis; thus, we eliminated wildlife inventories, mine reclamation activities, etc. We summarized the remaining 8,747 management activities into standardized transition classes such as prescribed burning, fuels treatment, and harvest thinning. As with the wildland fire transitions, we calculated average annual probability-per-hectare values for each PNVT and assigned these probabilities to each model state (table 4a). In a typical year during the sampled time period, 0.1 percent of the pinyon-juniper grassland PNVT was affected by these activities.

Insect and disease transitions—Both localized and widespread mortality events have occurred in the pinyon-juniper woodlands on the Coconino NF (Lynch and others 2007). These events have typically been pinyon ips outbreaks associated with periods of drought, such as occurred in the 1950s, and more recently in the mid-1990s and 2001-2003. Localized outbreaks resulted from range improvement projects that generated large amounts of fresh pinyon slash (Negrón and Wilson 2003; Yasinski and Pierce 1962). Although pinyon ips outbreaks can be severe, with pinyon mortality approaching 100 percent within a given stand, they are generally short lived (1-2 years). The pinyon ips outbreak during the late-1990s east of Flagstaff near Twin Arrows encompassed almost 5,261 hectares (13,000 acres) at its peak (Negrón and Wilson 2003).

At least within the historic period, the size and severity of the recent drought- and pinyon ips-related die-off is unprecedented for the Coconino NF and northern Arizona (Allen 2007; Mueller and others 2005). The contemporary pinyon die-off is 100 times as large (two orders of magnitude) as any previously recorded acreage for pinyon ips beetle mortality for the Coconino NF, Kaibab NF, and Grand Canyon National Park. High levels of pinyon mortality were detected by aerial survey during 2001 through 2003, with approximately 809,389 hectares (2,000,000 acres) impacted Region-wide and more than 60,704 hectares (150,000 acres) on the Coconino NF. The mortality was primarily attributed to pinyon ips attacking drought-stressed pinyon; however, twig beetles (*Pityophthorus* spp.) were also observed killing smaller pinyon in 2003. Pinyon mortality averaged 41.4 percent within an 80-km (50-mile) radius of Flagstaff, with mortality being significantly greater on southern aspects and shallow soils developed in volcanic cinders (Gitlin and others 2006).

Using data from the above insect and disease outbreaks, we calculated average annual probability-per-hectare values for each model state. These transition probabilities were assigned to each model state (table 4a).

Natural growth transitions in the absence of disturbance—To quantify the natural growth transitions that will occur in the absence of natural and anthropogenic disturbances, we used the PRESIDE software (Vandendriesche 2009) to process the outputs of FVS (Dixon 2002). In our case study, we show the results of applying this methodology in the Southwestern Region. The steps in this process include:

1. Prepare the FIA inventory data for projection by FVS: Each FIA plot for the PNVT in the Southwestern Region is assigned to the appropriate model state.
2. Perform FVS calibration steps: Calibration procedures include using the FVS self-calibrating feature, estimating and inputting natural regeneration response, accounting for tree defect for volume estimates, and determining tree species size attainment and limiting stand maximum density.
3. Run natural growth projections for each FIA plot using the calibrated FVS to simulate growth over a 250-year time period.
4. Process the tree list output through the PRESIDE post-processor classifier and accumulate the results into a matrix from which to estimate the average annual probability per hectare that in the absence of disturbance a plot will transition from one state to another state (table 4b).
5. Using the sample of plots populating each state at each point in time during the projection, summarize the vegetation characteristics of each model state (table 5). The post-processing software indexes the aggregate state classes to summary values derived from the tree lists and attributes from standard FVS outputs. Several dozen vegetation characteristics such as stand volume and stand carbon can be quantified for each model state.

Model runs—Model simulations from VDDT are non-spatial and reflect a summary of up to 50,000 sample units or *cells*. For our study, we opted for 1,000 sample units because our earlier work, and work conducted by TNC and LANDFIRE, indicated that this number produced reasonable and consistent projections (TNC and others 2006). If we increased the number of cells beyond 1000, results of the analysis would not be significantly changed, but running time would be increased significantly. In the next step of the modeling process, we initialized the starting hectares in each state based on current conditions indicated by mid-scale vegetation mapping data. We ran multiple simulations to estimate the long-term

Table 5—FVS Outputs.

Vegetation Structure Variables:							
VDDT State	**A _ GFB**	**B _ SSO**	**C _ SMO**	**D _ MVO**	**E _ SSC**	**F _ SMC**	**G _ MVC**
Dominance Type	PIED	PIED	PIED	PIED	PIED	PIED	PIED
Size Class	0	1	2	3	1	2	3
Canopy Class	0	1	1	1	2	2	2
Canopy Layers	1	2	1	1	1	1	1
Stand Age – Overstory	17	76	98	118	97	146	207
Stand Age – Dominant Story	0	55	92	130	68	121	196
Total Plot/Activity Count	323	277	317	1222	194	3084	9895
Stand-Stock Variables:							
Seedlings/Acre < 1.0” diameter	61	148	117	103	265	159	89
Trees/Acre = 1.0” diameter	206	441	395	286	777	493	315
Basal Area/Acre = 1.0” diameter	11	37	44	57	84	117	135
Quadratic Mean Diameter – Trees = 1.0” diameter	3	4	5	6	5	7	9
Quadratic Mean Diameter – Top 20 percent, diameter	0	7	9	14	8	11	15
Stand Density Index – SDI_Summation	20	90	94	99	195	233	235
Stand Density Index – SDI_Dq	30	106	111	128	221	260	263
Canopy Cover	6	21	22	21	40	48	48
Live – Cubic Feet/Acre	88	233	328	568	515	1176	1741
Live – Board Feet/Acre	0	5	12	16	30	18	11
Wildlife Habitat Variables:							
R3 – Vegetative Structural Stage	1	3ASS	4ASS	5ASS	1C	4CSS	5CSS
Standing Snags							
Small = 5-10” diameter	1.1	0.6	2.8	2.4	3.4	26.4	14.0
Large = 10”+ diameter	1.6	2.7	2.9	5.9	4.3	6.2	12.1
Extra-large = 18”+ diameter	0.7	1.2	1.3	2.8	1.5	2.0	2.6
Snag Recruitment							
Small = 5-10” diameter	0.2	0.4	2.0	0.9	4.9	26.0	11.4
Large = 10”+ diameter	0.5	1.3	1.0	2.5	2.4	3.5	7.5
Extra-large = 18”+ diameter	0.2	0.4	0.4	1.0	0.6	0.7	0.9
Pestilent Disturbance Variables:							
Dwarf Mistletoe Rating	0.04	0.09	0.14	0.15	0.22	0.34	0.41
Wildfire Risk Variables:							
Crown Bulk Density	0.00	0.02	0.02	0.01	0.04	0.04	0.03
Crown Base Height	4.5	4.7	6.2	7.6	4.9	5.7	7.5
Crowning Index	170.5	72.4	85.7	121.8	52.3	49.0	61.3
Torching Index	5.0	3.2	6.4	8.0	3.1	5.8	10.1
Fire Hazard Rating	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Fuel Load – Coarse Woody Debris = 0-3” diameter	0.1	0.4	0.5	0.6	1.2	1.7	1.5
Fuel Load – Coarse Woody Debris = 3-12” diameter	0.2	0.7	1.3	2.1	1.9	5.1	9.4
Fuel Load – Coarse Woody Debris = 12”+ diameter	0.2	0.8	1.3	2.0	1.2	3.1	5.2
Biomass-Carbon Variables:							
Tree Biomass – Dry weight live & dead/boles & crown	2.4	7.6	8.6	14.3	16.7	27.8	36.4
Stand Carbon – Total carbon above & below ground	2.8	7.2	8.5	12.4	14.8	24.9	32.6

effects of continuing current management under the existing land management plan. We ran ten simulations with each simulation projecting conditions annually for 200 years based on data and assumptions described earlier. We compared the average annual results of these simulations with current conditions and reference conditions (table 6)

Table 6—Proportion of area in pinyon-juniper grassland states in current and projected conditions.

Vegetation state	A	B	C	D	E	F	G	Percent departure	ECC
Current condition	23	1	13	27	0	17	19	34	2
Projected trends									
10 years	20	4	9	25	1	18	23	36	2
50 years	15	6	6	22	1	18	32	40	2
200 years	13	4	5	22	2	17	37	42	2

Results

Here we provide results to answer the question, "How do current and projected conditions compare to reference conditions?" Again, reference conditions were derived from VDDT models, developed by LANDFIRE, to quantify the historical proportion of major vegetation states of the pinyon-juniper grassland system (table 2). Current conditions and projected conditions are summarized in table 6.

Current conditions represent existing vegetation mapping synthesized according to the vegetation states contained in the pinyon-juniper grassland model. An ECC value of 34 indicates a system that is somewhat departed from reference conditions, on the low end of the moderate range. Current conditions indicate an uncharacteristic excess of grass-forbs communities (state A), an excess of closed woodlands (states B and E), and a reciprocal deficit of open woodlands (states C and D).

Likewise future projections indicate a continuing trend towards departure, from an index value of 36 at 10 years, to 40 at 50 years. If current management continues, departure from reference conditions as measured by Ecosystem Condition Class will increase over time due to more acres moving to the closed states.

These results relate to the ecological sustainability concepts stated in our introduction and restated more simply here: Every species around today persisted over time in its environment under reference conditions. If current and proposed future management creates or approximates that environment, then the species is not likely or is less likely to be at risk. On the other hand, as in this case study, if the ecosystem is departed from reference conditions, and if that departure increases over time, then both the ecosystem and its associated species are less likely to be sustainable.

Discussion

The Analysis Process

As mentioned, TNC, LANDFIRE, and others have made a significant investment in the development of reference condition descriptions and models. We've complimented these models with the development of calibrated and more detailed models that depict current trends and project future conditions. Current and future conditions can be compared with reference conditions to answer two questions: 1) is there a current departure from reference conditions, and 2) will conditions remain static, trend towards, or trend away from reference conditions? Trends away from reference condition may indicate an ecosystem at risk and, if so, the model can be further tooled to evaluate the potential effectiveness of management strategies.

Also, as discussed under Methods, in retooling the models, several assumptions were necessary in the face of uncertainties concerning the historic condition. While additional information is needed to supplement and refine concepts for the pinyon-juniper grassland PNVT, working assumptions on fire frequency and stand dynamics were necessary to enable useful modeling of the system. For example, we assumed that a plurality of tree diameters existed to indicate one of four tree-dominated states, acknowledging that multiple tree cohorts within any one plant community were likely due to fire frequency and productivity.

Evaluation of Results

Southwestern pinyon-juniper woodlands span a wide range of environmental settings over 8.6 million hectares (3.5 million acres), yet historical descriptions are extremely limited. The pinyon-juniper grassland type is thought to have been maintained historically by frequent, low-severity surface fires that spread from and into adjacent systems including semi-desert grassland, juniper grassland, and ponderosa pine forest. Some references (e.g., Gottfried 2003) suggest that the resulting stand structure would have been uneven-aged, dominated by open grown trees. Modern fire suppression and grazing would have since favored closed canopy structures susceptible to drought-insect induced mortality and uncharacteristic fire (stand replacement). The current surplus of grass-forbs communities has likely resulted from stand clearing and pasture development, and from increased drought-insect mortality and fire activity. Long term VDDT modeling based on current practices, as reflected in management records from 1988 to 2006, indicates the perpetuation of dense canopies with regular conversion to a grass-forbs state.

The objective of this paper is to illustrate through a case study how State-and-Transition Models (STMs) can be developed and used to evaluate the ecological sustainability of ecosystems. We accomplished this objective by using an empirical approach to create and calibrate our models based on existing inventory data and FVS simulations based on existing data; this allowed us to compare and contrast reference conditions, existing conditions and projected conditions to quantify the departure of existing and projected conditions from reference conditions.

Our analysis indicates that the pinyon-juniper grassland ecosystem on the Coconino NF is moderately departed from reference conditions and that this trend will continue into the future under the existing land management plan. Fire suppression coupled with infrequent forest management activities contributes to an existing departure from reference conditions. Thus, the continued current implementation of the existing land management plan may pose a risk to the ecological sustainability of this ecosystem.

Others such as Arno and Fiedler (2005) have explored deteriorated forest and woodland conditions in western North America and reached similar conclusions. By developing empirically based landscape dynamics models, we can quantify woodland conditions with more reliability to assess the ecological sustainability of these ecosystems within a more credible, systematic framework for strategic land management plans.

Addressing Carbon Accounting and Climate Change

Future extensions of our methodology include projecting the effects of climate change on ecological sustainability and providing spatial simulations (Miller 2007). We also advocate evaluating adaptive and mitigation strategies as outlined by Millar and others (2007).

Carbon accounting for mitigation strategies was provided by the carbon extension of the Forest Vegetation Simulator (Havis and Crookston 2008). Carbon accounting attributes are shown in table 7. Our results indicate that as the ecosystem moves further away from reference conditions over time (due to more acres moving into the closed states), the ecosystem sequesters more total carbon (above and below ground), because the closed states contain more stand carbon per acre than do the open states. This represents a trade off that must be evaluated by land managers: managing toward reference conditions versus managing to maximize short-term carbon sequestration.

The long-term sustainability of these uncharacteristic closed states is dependent upon insect, drought, and fire occurrence. For example, as closed canopy states are removed by wildfire, the sequestered carbon is released to the atmosphere. Sequestration of excess carbon in closed canopy states in frequent-fire adapted forest types may result in a net long-term loss of carbon sequestration values when uncharacteristic stand-replacing fires occur (Hurteau and others 2008).

The current model does not provide for charcoal or soil organic carbon, though future analyses are likely to include these components (DeLuca and Aplet 2008; Jenkins and others 2003). The amount of soil carbon in the pinyon-juniper woodlands is significant; it can be up to 8 tons per acre in the A horizon and up to 12 tons per acre in the total solum (Meurisse and others 1991). The amount of organic carbon in soils within the pinyon-juniper woodlands is inherently lower than higher elevation montane forest types (Meurisse and others 1991).

Adaptation strategies necessitate predictions about future vegetation patterns and at this time, we are considering the advantages and disadvantages of alternative approaches to modeling climate change. The assumptions in our projection

Table 7—Thousands of tons of stand carbon occurring above and below ground.

Vegetation state	A	B	C	D	E	F	G	Total
Current condition	194	22	333	1,010	0	1,277	1,869	4,705
Projected trends								
10 years	169	87	231	935	45	1,352	2,262	5,081
50 years	127	130	154	823	45	1,352	3,147	5,778
200 years	110	87	128	823	89	1,277	3,639	6,153

[a] Stand carbon per acre is taken from table 5 and does not reflect charcoal or organic soil carbon. Acres are taken from table 6.

models can be modified in the following ways to incorporate the emerging evidence from climate research (Hemstrom and Merzenich, unpublished document):

1. Types of states: Climate change may result in the addition or removal of states within a PNVT as new vegetation composition and structural patterns are introduced with changing site potential and processes (such as the introduction of exotic species).
2. Types of transitions: Climate change may result in the addition or removal of transitions within a PNVT, with novel patterns of vegetation composition, structure, and process.
3. Rates of transitions: The rates of transitions between model states for existing transitions, for example, stand replacing fire, may change within the PNVT and planning area.
4. New (adventive) PNVTs: Adventive PNVTs may need to be modeled, depending on the climate scenario.
5. Transitions between PNVTs: In addition to transitions *within* PNVT models, transitions *between* PNVTs may be necessary to reflect the movement of area between PNVT classes as climate changes.
6. New management activities: New management activities may be necessary to respond to adaptive and mitigation strategies (Millar and others 2007), along with modification to the rates of existing transitions.
7. Projected climate variability: Changes in the annual variation of phenomena such as wet years, dry years, insect and disease incidence, etc. may be explicitly modeled within existing VDDT software.
8. Addressing multiple climate scenarios: Current assumptions can be modified to reflect each climate change scenario that needs to be considered by management; for example in scenario 1 the planning area may be getting warmer and drier, and in scenario 2 the planning area may be getting warmer and wetter.

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