Using State-and-Transition Models to Project Cheatgrass and Juniper Invasion in Southeastern Oregon Sagebrush Steppe

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Abstract

Many threats are jeopardizing the sagebrush steppe of the Columbia Basin, including the spread of invasive species such as cheatgrass (*Bromus tectorum* L.) and the expansion of western juniper (*Juniperus occidentalis* Hook.) into historic shrub steppe. Native sagebrush steppe provides productive grazing lands and important habitat for many wildlife species, and managers are in need of landscape-scale tools to assess shrub steppe conversion risk and management options to maintain native shrub steppe. We used a state-and-transition modeling approach to project changes in sagebrush steppe vegetation across the landscape of southeastern Oregon. Models were constructed using both empirical data, including empirically derived fire probabilities, and expert opinion for processes that are still poorly documented, such as livestock grazing effects. With unrestricted grazing and no restoration treatments, future invasion by exotic annual grasses in warm, dry sagebrush steppe and juniper expansion into cool, moist sagebrush steppe are likely to accelerate in the next 50 years under current climatic conditions. Invasions are also likely to be spatially heterogeneous, depending on the mix of sagebrush steppe environments, current rangeland condition, disturbances, and management activities across the landscape. We conclude that state-and-transition models provide a useful framework for conceptualizing vegetation dynamics of sagebrush steppe systems, identifying gaps in knowledge, projecting future vegetation conditions, and identifying potential areas for restoration at landscape scales.

Keywords: *Bromus tectorum*, cheatgrass, invasive species, western juniper, *Juniperus occidentalis*, rangeland, sagebrush steppe, state-and-transition modeling.

Introduction

Sagebrush steppe ecosystems across much of the West have experienced significant declines over the last few decades (Connelly et al. 2004, Hemstrom et al. 2002). Among the major threats, intensive livestock grazing, species invasions, altered fire regimes, development, and climate change are all thought to contribute to the decline of shrub steppe (DiTomaso 2000, Jones 2000, Mack 1981, Miller et al. 2005). Rangelands provide an important source of forage for livestock, and degradation of shrub steppe may reduce the ability of rangelands to support livestock (Belsky 1996, Young and Clements 2009). Conversion of sagebrush steppe also occurs against a backdrop of increasing concern about loss of habitat for sagebrush-obligate species such as greater sage-grouse (*Centrocercus urophasianus*) (Connelly et al. 2004). Restoration of degraded shrub steppe can be exceedingly difficult due to the complex and often unpredictable interaction of site potential, fire, climate, invasive species, and management practices such as grazing (Di-Tomaso 2000, McIver and Starr 2001).

Exotic species invasions and native juniper expansion in particular have dramatically changed the landscape in eastern Oregon over the last century. Exotic annual grasses, such as cheatgrass (*Bromus tectorum* L.), ventenata (*Ventenata* Koeler spp.), and medusahead (*Taeniatherum caput-medusae* (L.) Nevski), have invaded many warm-dry sites, and have changed the vegetation structure and fire regime by forming dense, dry grass stands and promoting frequent fire (Pellant 1996, Whisenant 1990). Another contemporary threat to shrub steppe ecosystems comes from expansion of western juniper beyond its historic range. Western juniper (*Juniperus occidentalis* Hook.) is native to eastern Oregon but has expanded rapidly in the past 130 years due to fire suppression, reduction of fuels from livestock grazing, changes in precipitation patterns, and other factors (Burkhardt and Tisdale 1976, Miller et al. 2005). Juniper trees can deplete soil water, alter species composition and biodiversity of shrub steppe, increase soil erosion, reduce stream flows, and reduce forage production for livestock (Miller et al. 2000, 2005). Because of these complex threats and the vast extent of shrub steppe ecosystems, there is a need for a broad, multi-ownership perspective to examine landscape-scale trends in vegetation and effects of rangeland management.

One approach to examine vegetation dynamics, natural disturbances, and management across large areas is through the use of state-and-transition models (STMs). STMs are widely used in land management across both forest and rangeland landscapes (Forbis et al. 2006, Hemstrom et al. 2004, Holmes et al. 2010, Weisz et al. 2010). The models provide a conceptual framework for understanding ecological dynamics (Bestelmeyer et al. 2009, Briske et al. 2006, Stringham et al. 2003, Westoby et al. 1989), and challenge ecologists to define their assumptions in terms of vegetation composition (states and phases) and processes that cause vegetation change (transitions). In the process of building STMs, existing literature and data can be explored and gaps in our knowledge and data are revealed as areas for future study. STMs allow the user to easily test alternative hypotheses about vegetation dynamics and change by evaluating different models, and allow managers to compare alternative management strategies in terms of desired outcomes. In this study, we construct a suite of detailed STMs designed to capture the contemporary dynamics of southeastern Oregon shrub steppe ecosystems, and use them to project vegetation change 50 years into the future.

We focus on two major sagebrush steppe ecosystems of southeastern Oregon. The most common sagebrush sites in southeast Oregon are warm, dry lowland sites (called warm-dry sites) primarily occupied by Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle and Young), basin big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata*), bluebunch wheatgrass (*Pseudoregeneria spicata* (Pursh) A. Löve), Thurber needlegrass (*Achnatherum thurberianum* (Piper) Barkworth), and needle-and-thread (*Hesperostipa comata* (Trin. and Rupr.) Barkworth). In these areas, exotic annual grasses have invaded many sites and partially or wholly converted the shrub steppe to exotic grass. The second major sagebrush system is characterized by cool, moist upland sites (called cool-moist sites) primarily occupied by mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle), low sagebrush (*Artemisia arbuscula* Nutt.), Idaho fescue (*Festuca idahoensis* Elmer), and bluebunch wheatgrass. Cool-moist sagebrush sites are more productive and less susceptible to invasion by exotic grasses, but many are rapidly converting into woodlands as western juniper expands its range. As part of the Integrated Landscape Assessment Project (ILAP), we project changes in sagebrush steppe vegetation under unrestricted livestock grazing and no restoration treatments, and focus on cheatgrass and juniper invasion as indicators of contemporary landscape change.

Methods

Study Area

We modeled sagebrush steppe vegetation types across a 5.3 million hectare (13.2 million acre) portion of southeastern Oregon, bounded by the Blue Mountains to the north and the foothills of the Cascade Mountains to the west (fig. 1). This area roughly corresponds to the Malheur High Plateau, Humboldt Area, and Owyhee High Plateau Major Land Resource Areas (MLRA) that are contained within the state of Oregon. The study area was comprised primarily of warm-dry sagebrush sites (59.8 percent) and cool-moist sagebrush sites (18.8 percent), with salt desert shrub, woodlands, playas, and other minor systems comprising

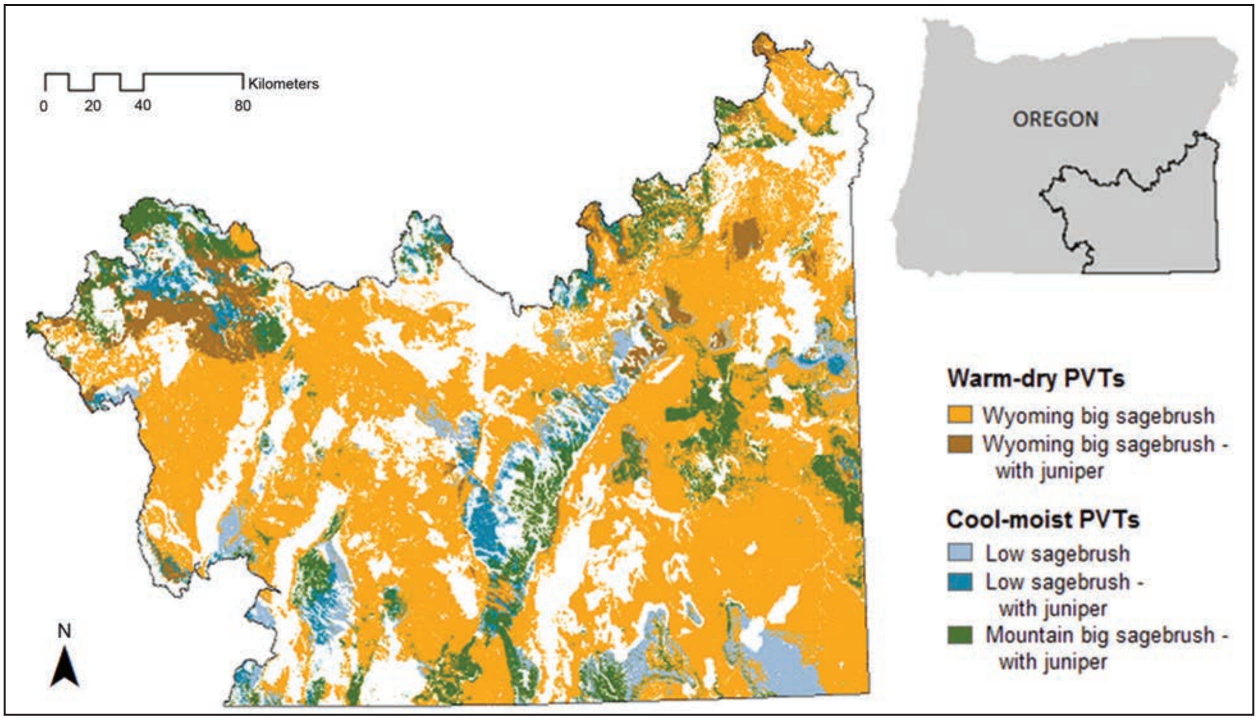

Figure 1—The sagebrush steppe in southeastern Oregon is divided into two major site types and five potential vegetation types (PVTs). Blank (white) areas represent other PVTs not modeled for this study, barren areas, urban areas, or agriculture.

the remaining undeveloped landscape. The Bureau of Land Management (BLM) was the primary land steward in the region, covering 72.7 percent, followed by private land and state agencies.

Spatial Layers

Three spatial layers were used to define our modeling units: potential vegetation type (PVT), ownership/allocation, and watershed. PVT described the vegetation potential of a site based on soils, climate, and disturbance regime. PVTs defined the spatial extent of each vegetation type as a modeling unit, and each STM simulated vegetation dynamics of alternative vegetation communities within a single PVT. We modeled five major PVTs, including two warm-dry types (Wyoming big sagebrush with and without juniper encroachment potential), and three cool-moist PVTs (mountain big sagebrush with juniper encroachment potential and low sagebrush with and without juniper encroachment potential) (fig. 1). Where plot data did not differentiate subspecies of big sagebrush, an elevation cutoff of 1200 m was applied, assuming that the mountain subspecies would occur above this elevation and the Wyoming subspecies would occur below this elevation. Potential vegetation was modeled using a random forest nearest neighbor imputation (RFNN) method (Crookston and Finley 2008, Ohmann and Gregory 2002), which related plant association data to grids of climate (PRISM climate group, Oregon State University) and topographic (National Elevation Dataset) environmental variables. Because projections of future vegetation condition must allow for expansion of juniper beyond its historic range, Wyoming big sagebrush and low sagebrush PVTs were divided into areas with and without potential for juniper encroachment in the PVT map using RFNN predictions of juniper cover. Mountain big sagebrush was considered susceptible to juniper invasion across its entire extent. All PVTs in this study were considered as sagebrush steppe potential, and thus any juniper presence was considered to be expansion beyond its historic range. The second spatial layer used to define modeling units was ownership/allocation, which categorized the landowner or land steward (BLM, Forest Service, private, tribal, state, and other) and management intent, ranked into five categories based on the intensity of intended use. For this study, the same STMs were run across all ownership/allocation levels, but the ownership/allocation layer will be used to inform varying grazing and restoration treatment levels for future studies. Third, we used 5th-field (10 digit) Hydrologic Unit Codes (HUCs) to define watersheds, downloaded from the United States Geological Survey (http://water.usgs.gov/GIS/huc.html). The combination of PVT, ownership/allocation, and watershed thus provided the spatial basis of our modeling, allowing us to stratify our model output in terms of site characteristics, management intent, and hydrologic unit location.

Additionally, we initialized our STMs with spatial maps of current vegetation. Current vegetation was modeled using a RFNN method. The mapping method was similar to PVT mapping, but in this case the RFNN method imputed field plot data to pixels using the association between field data (species composition and cover), grids of environmental data, and LANDSAT TM (thematic mapper) imagery from 2000. Vegetation communities in the current vegetation map were linked to states and phases in the STMs using a series of rule sets that allocated every pixel in the landscape into a state or phase.

State-and-Transition Models (STMs)

We constructed STMs using the Vegetation Dynamics Development Tool (VDDT) (ESSA Technologies 2007) to characterize vegetation dynamics of the major sagebrush ecosystems in southeastern Oregon and project future vegetation change. VDDT allows users to divide the landscape into distinct combinations of vegetation cover and structure (states and phases), linked together by processes (transitions) such as succession, disturbance, and management activities. Users define a pathway for each transition and its annual probability of occurring, and VDDT uses Monte Carlo simulations to project landscape change over time. VDDT is a non-spatial model, and tracks each simulation cell independently of neighboring cells. Simulations were run in the Path Landscape Model (Apex RMS and ESSA Technologies), which uses VDDT as a simulation engine but allows the user to run multiple STMs and scenarios (such as alternative management options) in a single landscape analysis.

One STM was constructed for each PVT, describing alternative vegetation states and phases within each potential vegetation unit. STMs developed by the BLM for the Malheur High Plateau MLRA in southeastern Oregon (Evers 2010) and STMs built by the USDA Forest Service for the Blue Mountains of northeastern Oregon[1] were used heavily to aid in constructing and parameterizing models. Conceptually, our sagebrush STMs can be divided into a few broad states (large boxes, fig. 2), with community phases (smaller boxes within states, fig. 2) describing varying combinations of cover and structure (Bestelmeyer et al. 2009). Major states include shrub steppe, exotic grass, juniper woodland, juniper with exotic grass, and seeded grass. Semi-degraded phases represent disturbance-impacted vegetation that is recoverable to native conditions (dashed lines, fig. 2) but is at-risk of crossing a threshold to an alternative state. Note that each STM varies; not all states and phases in figure 2 are present in each model, and transition probabilities vary substantially among STMs, particularly between PVTs on warm-dry and cool-moist sites.

Specific criteria were used to define the vegetation composition and structure of each state and phase within each STM. Herbaceous composition was used as an indicator of native, semi-degraded, or exotic-dominated condition. Exotic grass states were defined by a minimum absolute and relative cover of exotic annual grasses, primarily cheatgrass and other invasive bromes, ventenata, medusahead, vulpia (*Vulpia bromoides* (L.) Gray), and others. Native states were defined by a minimum absolute and relative cover of 8 grass species sensitive to disturbance (decreasers such as bluebunch wheatgrass, Idaho fescue, needle- and-thread, some *Achnatherum* and *Elymus* species, and others). Cover

[1] Personal communication: Dave Swanson, former area ecologist, USDA Forest Service, Baker City, OR.

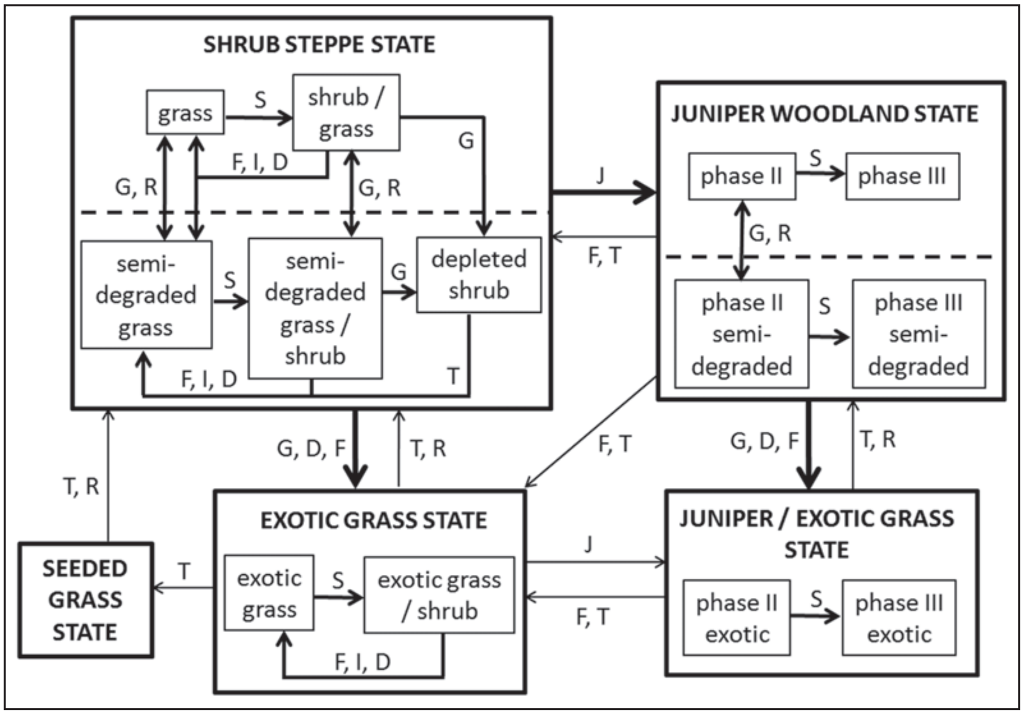

Figure 2—A conceptual state-and-transition model (STM) diagram of vegetation dynamics in the Wyoming big sagebrush with juniper potential vegetation type (PVT), showing major model states (large boxes), representative phases within states (small boxes), and transitions that link states and phases (arrows). Transitions include succession (S), fire (F), juniper establishment (J), grazing (G), insect outbreaks (I), drought (D), recovery (R), and management treatments (T). Dashed lines separate native from semi-degraded condition, and represent reversible thresholds where recovery to native condition is more likely. Transitions between states, however, are often irreversible without management intervention or major disturbance, and low probability recovery transitions are shown as thin arrows. Juniper phases II and III represent increasing juniper dominance (Miller et al. 2005), and phase I juniper woodlands are omitted for simplicity. Each individual STM varies and this figure represents a simplified model for a single PVT.

thresholds are variable among models. In PVTs where seeding of nonnative species occurs, seeded states were defined by *Agropyron* species and others that are commonly seeded in rangelands. Anything that did not meet the minimum threshold for these indicator species was considered to be in a semi-degraded state. Depleted shrub was defined as high shrub cover (≥25 percent) and low grass cover (<5 percent) and is only present in warm-dry sagebrush models. Juniper woodlands were divided into phases I, II and III based on Miller (2005), where phase I represented shrub steppe with scattered juniper, phase II represented codominant juniper and shrubs/grasses, and phase III indicated mature woodlands where juniper was dominant. Juniper cover classes of 2–10 percent, 11–20 percent and >20 percent were used to distinguish phases I, II and III, respectively, based on feedback from expert reviewers.

Disturbance dynamics, including succession, natural disturbance (e.g., wildfire, drought, and insects) and management transitions (e.g., seeding, cutting, and prescribed fire) were modeled by specifying transition pathways between boxes and defining annual probabilities of growth or disturbance events occurring (table 1). Models were constructed so the primary mechanism for degradation (exotic grass invasion) into sagebrush steppe was through the interaction of grazing with fire or drought disturbance (Curtin 2002, Evers 2010, Loeser et al. 2007). In warm-dry sites, recovery of native species in exotic grass states was slow and required rest from grazing disturbance before it

Table 1—Transitions used to model sagebrush steppe vegetation dynamics in southeastern Oregon

Transition	Description
Replacement fire	Wildfire that results in return to early-successional phases. Replacement fire is modeled in all states and phases.
Mosaic Fire	Patchy fire that thins shrubs or trees. Mosaic fire occurs in most phases except those dominated by exotics, closed or depleted shrub, and phase III juniper.
Surface fire	Surface fire that burns the woodland understory (phase III juniper with exotic grass only).
Maintenance grazing	Low-impact grazing that does not affect plant community composition or structure.
Moderate grazing	Grazing that causes successional change by increasing shrub cover but is not severe enough to promote exotic grass invasion.
Graze degrade	Heavy grazing that causes degradation from native to semi-degraded to exotic grass-dominated shrub steppe. The transition probability is low, as we assume that the interaction of grazing with disturbance (Post-disturbance graze degrade) is more likely to lead to degradation.
Post-disturbance Graze degrade	Heavy grazing after major disturbance, leading to semi-degraded condition or exotic grass-dominated states. This transition can only occur within two years following a fire or drought, and the transition probability is 10-fold higher than Graze degrade.
Drought	Moderate multi-year drought that does not cause vegetation change.
severe drought	Drought severe enough to kill shrubs, causing a transition to early-successional shrub steppe. This transition occurs only once every 100-200 years.
Natural regeneration	Recovery of native herbaceous vegetation in a degraded site by natural regeneration. This transition usually requires rest from grazing to occur.
Juniper establishment	Juniper establishment that converts shrub steppe to phase I juniper.
Insect Outbreaks	Cyclical outbreaks of sagebrush-defoliating insects, occurring once occur every 20-30 years.

would begin to occur. In cool-moist sites, recovery from exotic grass states was modeled to occur automatically unless it was heavily grazed, reflecting the higher competitive ability of native bunchgrasses in mesic sites. Fire probabilities varied among states and phases based on the cover of exotic grass species (see “Fire Probabilities”). Insect outbreaks and severe drought affected vegetation by thinning shrub cover, and juniper establishment events (where applicable) occurred from late-successional shrub steppe into phase I woodlands (Evers 2010). Management transitions were built into the models but were deactivated for this study to evaluate future landscape condition without active management.

Fire Probabilities

We used the Monitoring Trends in Burn Severity (MTBS) data to derive fire probabilities and interannual variability in fire year (Eidenshink et al. 2007, www.mtbs.gov). The MTBS data set is a publicly-available, 25-year record of all fires >405 hectares (>1,000 acres) in size across the United States from 1984 to 2008. It includes fire perimeters and burn severity ratings for each fire occurring in the study area from 1984 to 2008. For this study, we used fire perimeters for ~250 fires to infer the proportion of the landscape in each PVT group burned annually. We overlaid the yearly maps of fire perimeters with a map of PVT groups (warm-dry and cool-moist) and exotic grass cover groups in a GIS. Exotic grass cover was derived from our current vegetation map, and divided into three groups: 0-10 percent, representing places with little to no invasion; 10-25 percent, representing areas that are semi-degraded; and >25 percent, where exotic grasses dominate the herbaceous layer. We extracted the landscape proportion burned and calculated annual fire probabilities for each combination of PVT group and exotic grass group (table 2), and assigned these probabilities to wildfire transitions in the STMs. Fire return intervals (FRIs) were calculated as the inverse of fire probability.

Running Simulations

Simulations were run in the Path model to project vegetation change 50 years into the future. One model was run for

Table 2—Annual fire probabilities and corresponding fire return intervals derived from Monitoring Trends in Burn Severity (MTBS) data for the two major sagebrush steppe site types and three levels of exotic grass cover. Numbers reflect fire return intervals under current levels of fire suppression

Site Type	Exotic grass cover	Annual probability	Fire return interval
Cool-moist sagebrush steppe	0-10 percent	0.0068	148
	10-25 percent	0.0089	112
	>25 percent	0.0173	58
Warm-dry sagebrush steppe	0-10 percent	0.0063	160
	10-25 percent	0.0114	88
	>25 percent	0.0179	56

each modeling unit (combination of PVT, watershed, and ownership/allocation). Where modeling units were <405 hectares (<1,000 acres) in size, a rule set was applied to combine small units within a watershed with other similar vegetation or management types. Where small units did not meet the criteria to combine with others, they were dropped from the analysis. The study area consisted of 889 modeling units in the major sagebrush steppe PVTs that were large enough to be retained for analysis, with <5 percent of the landscape not modeled due to small modeling unit size. Each STM was run for 30 Monte Carlo simulations with random draws of fire severity year and insect outbreak occurrence, and we reported average trends.

Model Output

To simplify results for graphical purposes, we combined states and phases into seven groups, including native, semi-degraded, and exotic shrub steppe, exotic grass, and phase I, II, and III juniper. Seeded states were not included for simplicity. Although VDDT is a non-spatial model, current and future projections of exotic grass and juniper woodlands can be summarized and mapped back to our spatial modeling units. We summarized the percent of pixels within each modeling unit that contained exotic grass or juniper woodland states, and displayed a single value scaled between 0 (low invasion level) and 1 (high invasion). Exotic grass maps displayed all exotic grass phases, and juniper woodland maps depicted woodlands in phases II and III only, since phase I juniper is similar to sagebrush steppe.

Results

Current and Projected Future Conditions

Our imputed current vegetation conditions (2000) for warm-dry sites across the extent of the study area indicate that much of the sagebrush steppe (~70 percent) was semi-degraded, with exotic grass encompassing ~15 percent of the landscape. In cool-moist sites, current vegetation maps show that half of the landscape was semi-degraded shrub steppe, one-third was native shrub steppe, and juniper encroachment affected <15 percent of the cool-moist shrub steppe. Where juniper had encroached it was still largely in phase I, with shrubs and grasses still dominant.

STM projections to year 2050 indicate a decline in rangeland condition in both warm-dry and cool-moist sites, assuming unrestricted grazing and no restoration treatments (fig. 3). Much of the current semi-degraded sagebrush steppe is projected to convert to exotic grass, increasing to nearly half of the landscape in warm-dry sites. In cool-moist sites, model projections indicate an increase in juniper woodlands to more than half of the extent of cool-moist PVTs, with rapid expansion of phase I in the first 25 years and conversion to phase II in the second half of the simulation. In both site types, native and semi-degraded shrub steppe decline as they are converted to exotic grass or juniper woodlands.

Invasion Maps

STM projections suggest that much of the landscape is likely to convert to either exotic grass or juniper woodland,

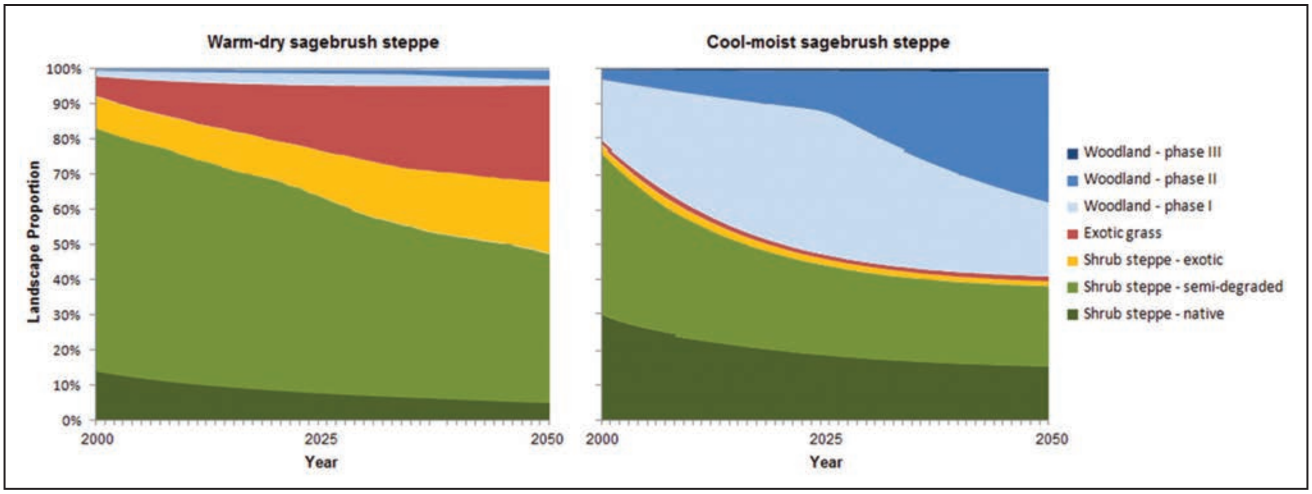

Figure 3—Projected vegetation change from 2000-2050 for warm-dry sagebrush steppe (left) and cool- moist sagebrush steppe (right). Graphs show average modeled landscape proportion across 30 Monte Carlo simulations for southeastern Oregon.

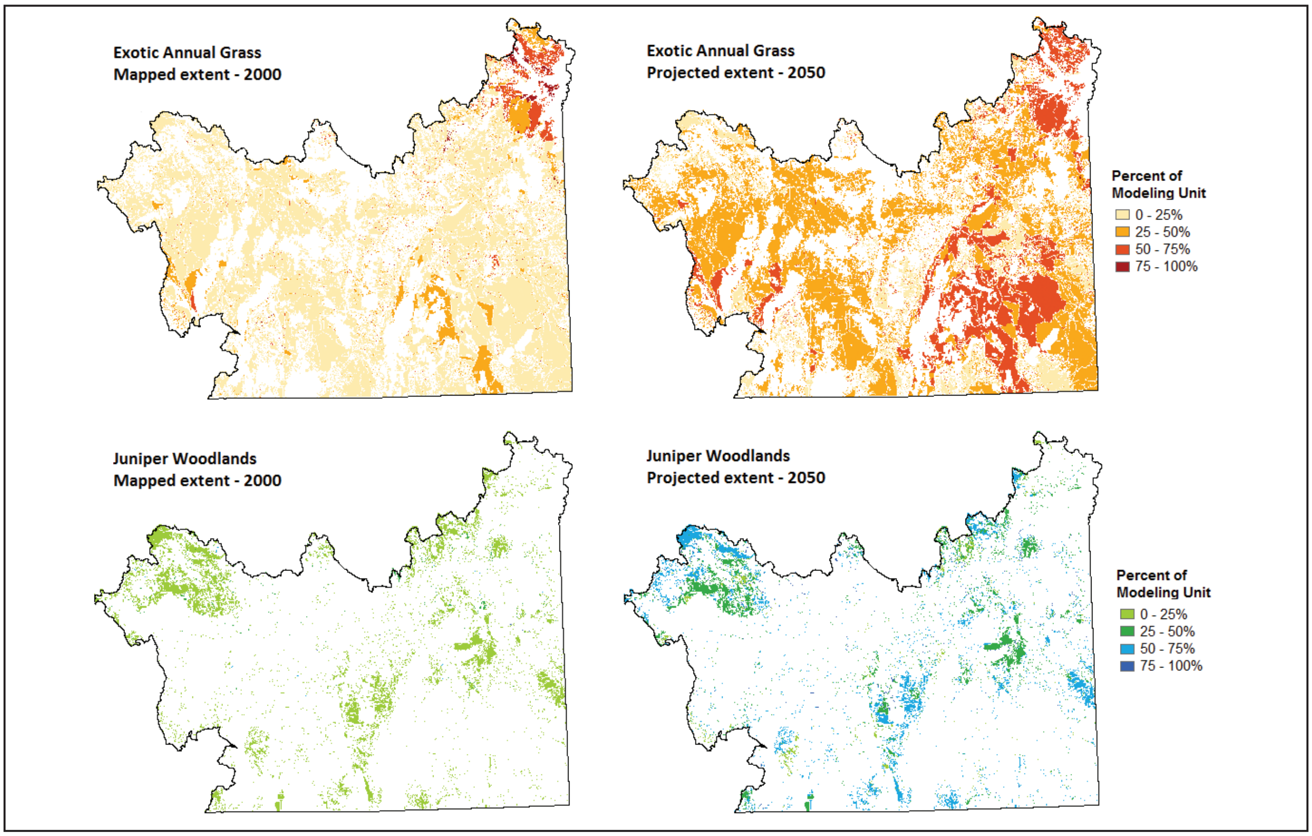

Figure 4—Exotic annual grass (top) and juniper woodlands (bottom) as mapped in 2000 (left) and projected for year 2050 using state-and-transition models (right). Colors depict the percent of each mapped modeling unit in an invaded state. Blank (white) areas were not modeled or represent PVTs where invasion cannot occur.

but that the severity of invasion is highly variable across the landscape (fig. 4). We report results at the modeling unit level because the STMs are non-spatial, and thus pixel-by-pixel projections are not possible.

Discussion

Model projections indicate that much of the sagebrush steppe landscape of southeastern Oregon is likely to experience invasion by exotic grasses or juniper under a scenario of unrestricted grazing and no restoration treatments. Exotic grass in particular is projected to expand across a large extent of southeastern Oregon, whereas juniper is more limited by site potential in drier (warm-dry) sites. However, these projections represent a worst case scenario, and managing grazing (particularly by limiting grazing during and after major disturbances such as fire and drought) or implementing restoration treatments could result in much improved landscape condition. Invasion risk maps show that the projected level of exotic grass and juniper invasion is highly heterogeneous across the landscape of southeastern Oregon. This heterogeneity stems from varying susceptibility of each PVT to invasion and variation in current vegetation condition at the initialization of the model runs (year 2000 conditions). Although the maps provide coarser-scale projections summarized at the modeling unit level instead of individual pixel-by-pixel predictions, they can nonetheless aid in large landscape-level assessment of rangeland condition and invasion risk, and provide a broader context for management decisions and prioritization across the study area.

The trends in exotic grasses largely reflect grazing effects and the interaction between grazing and major disturbance (fire and drought). We assumed that heavy grazing in warm-dry sites leads to degradation by reducing the presence of native grasses while providing a competitive advantage to nonnative species, which is exacerbated under conditions of abiotic stress. Under heavy grazing, a feedback loop is created whereby grazing leads to more exotic grasses, which in turn leads to more frequent wildfires, and leads to an even greater exotic grass presence. Furthermore, once range condition has deteriorated to semi-degraded conditions, some disturbances even in the absence of grazing can lead to dominance by exotic grasses. Grazing also removes grasses in sites that are susceptible to juniper invasion, which provides greater opportunity for juniper establishment under existing shrubs and reduces fuel that would historically cause establishing juniper woodlands to periodically burn (Burkhardt and Tisdale 1976, Miller and Wigand 1994). Much of the landscape that was historically shrub steppe is now considered to be vulnerable to future juniper expansion (fig. 1), and our projections suggest rapid juniper expansion, as has been documented on many of these sites (Miller et al. 2005).

STMs have been adopted by many land management agencies because of their useful characteristics for organizing ecological knowledge and informing management. They provide a relatively simple and intuitive modeling framework that managers can use as a mid or broad-scale land management tool. STMs can be used as conceptual models as well as predictive models, and they force ecologists to formalize their assumptions about landscape dynamics. They are easily incorporated into sensitivity analysis to test the importance of different processes under a certain set of assumptions, and can challenge and expand ideas about rangeland ecosystem dynamics and management. Constructing models can also be valuable for highlighting areas where little empirical data exists. We used a variety of data sources to construct our STMs, including empirical data to construct fire probabilities (Eidenshink et al. 2007) and drought frequencies (Knapp et al. 2004), published (Evers 2010) and unpublished STMs, and several experts to construct our models. The STM framework can readily accommodate new data and information as it becomes available to test our assumptions and understanding of sagebrush steppe ecosystems.

A novel aspect of our study was the inclusion of MTBS fire perimeter data to quantitatively derive fire return intervals for each site type and varying levels of exotic annual grass invasion (table 2). It was particularly important to capture the effects of exotic grass in our analysis, since exotic grasses can dramatically increase fire frequency and severity (Pellant 1996, Whisenant 1990) and fire probabilities are expected to vary among states and phases in the STMs. Our analysis assumes a similar level of exotic grass cover over the 25-year record, but is likely to be more robust to interannual variability in grass productivity and cover since we group exotic grass cover into three broad categories. Consistent with previous studies, we detected an increase in fire with increasing exotic grass cover, although fire return intervals are not as frequent as some previous studies suggest (Evers 2010, Pellant 1996, Whisenant 1990). Because the MTBS record has captured fires under a fire suppression policy, our model projections assume a fire suppression policy and effectiveness similar to that of recent decades. The MTBS data provides the most detailed spatial record of wildfire occurrences we are aware of, but it is likely that wildfires are underreported to some degree, particularly on nonfederal lands and earlier in the recorded history (1980s). Although the MTBS data set has several limitations, we maintain that the benefits of using over two decades of spatial, quantitative data outweigh the limitations of the data set.

Although STMs have proven useful to many land managers and rangeland scientists, various drawbacks to the approach limit the interpretations we can make with STMs. Non-spatial STMs by nature cannot model spatial processes explicitly or incorporate fine-scale site variation, resulting in generalized predictions that can only be applied at mid to broad spatial scales. STMs are also not mechanistic, and rely upon the modeler to determine the effects of disturbance and management processes and how they cause state and phase change. Most STMs, including those presented here, rely at least in part on expert judgment to determine transition pathways and probabilities, and therefore each expert will likely build a slightly different model. Even where some data are available, it is generally not available across large landscapes, adding uncertainty about the effects of environmental heterogeneity on transition probabilities. Given these limitations, we frame STMs as working hypotheses that describe the state of the knowledge about each ecological system given various assumptions. They are designed to conceptualize and project vegetation dynamics across broad spatial scales, and should be coupled with field studies to refine local vegetation dynamics where possible. Lastly, our models do not address climate change effects, as our projections are relatively short-term (to year 2050), but methodology is being developed as part of ILAP to incorporate climate change effects in our STMs (Kerns et al. 2012).

In this study, we demonstrate the utility of STMs for evaluating the risk of sagebrush steppe conversion to exotic grass or juniper across the landscape of southeastern Oregon. Although we projected large increases in both exotic grasses and juniper, we only ran a worst-case scenario of no restoration treatments and unrestricted grazing. With the models and data available we can now begin to incorporate alternative management scenarios to address a range of questions such as: given a limited budget, what combination of fuel treatments, seeding, grazing levels, and/or juniper control could maintain or improve current levels of good condition sagebrush? Where should we prioritize such treatments? How do our projections relate to habitat for species such as sage-grouse? How might our answers differ under a changing climate? The resulting projections and maps of model output can be useful to public and private land managers in answering important management questions and providing a broader context for landscape treatments and restoration.

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