University of Nevada, Reno

Calibration of a new zone for the SIMulating Patterns and Processes at Landscape scaLEs (SIMPPLLE) model for the Great Basin

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by

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Abstract

A new zone was created for the SIMulating Patterns and Processes at Landscape scaLEs (SIMPPLLE) model for vegetation simulations in the hydrologic Great Basin. Current parameterization is designed to use LANDFIRE data as input. Three separate mountain areas were considered for this study: the Clover Mtns., the Sheep Range, and the Snake Range. Fire histories for each area were based on an eleven year period (1986-1996), and were acquired from the National Fire Occurrence database. Ten-year calibration simulations were performed for each mountain area using 1999 vegetation data to initialize the run. Vegetation data from 2008 was used to assess the simulated end states. Model pathways were adapted to the Great Basin ecosystems, successional stages, disturbance processes, and ecoclimatic features. The model performed well at predicting vegetation type, but was inconsistent predicting canopy cover density and canopy height.

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1 Introduction

Landscape-scale vegetation patterns throughout the western U.S. are shaped by climate, topography, geology and disturbance processes (Turner 1989). Disturbance processes are integral components of ecosystem ecology, and include fire, insect and disease, climatic disturbances, and human activity. Disturbance processes are not isolated from climate, succession, or other ecosystem processes (Taylor and Beaty 2005). The trajectory of one type of disturbance event can be affected by other recent, or co-occurring, disturbance events (Larsson et al. 1983, Mutch and Parsons 1998, Fettig et al. 2010); indeed, a disturbance can increase the likelihood, or even initiate, other disturbances. For example, drought can kill some trees directly (Breshears et al. 2009), it can increase susceptibility of trees to insect infestations (Shaw 2006, Floyd et al. 2009), and also increase the likelihood of severe fires. Disturbance regimes also change over time in forested landscapes of the western U.S. (Swetnam and Baisan 1996, Shaw et al. 2005, Breshears et al. 2009, Romme et al. 2009). Climatic processes can alter disturbance events directly, e.g. by changing frequency of lightning strikes for wildfire ignition; or indirectly, by affecting the environment of disturbance agents such as bark beetles or by increasing or decreasing undergrowth and fine fuels for fire (Raffa et al. 2008).

Drivers of vegetation dynamics such as fire, climate, and succession contribute to ecosystem change. Fire is a relatively brief, periodic disturbance that can maintain or initiate an ecosystem, depending on spatial scale and severity. Plant response to wildfire, especially considering invasive non-native species, also plays an important ecological role. Climatic conditions that allow the growth of fine fuels influence the amount of area burned in arid ecosystems (Littell et al. 2009). Within a year or two after experiencing climatic conditions that are favorable for growth of herbaceous plants, the increase in fine fuels leads to an increase in the acreage burned. For the years between 1977 and 2003, Littell et al. (2009) found that the most important factors for predicting area burned in mountain ranges of east-central Nevada were precipitation and growing season temperature in the two years prior to the fire season.

Climate drives ecosystem processes in many ways. Throughout the Great Basin climate is considered to be typical of a cold desert (Miller et al. 2008); however, the effects of spatial variation in temperature and precipitation that are related to elevation, latitude and longitude are readily seen in vegetation differences (Charlet 1996). Basins are typically sagebrush (*Artemisia spp.*) shrublands, but with increasing elevation, vegetation ranges through pinyon-juniper (*Pinus monophylla* Torr. & Frem.-*Juniperus osteosperma* Torr.) woodland, mountain mahogany (*Cercocarpus ledifolius* Nutt.) woodland, mixed coniferous forest and into low sagebrush shrubland above treeline. Precipitation and temperature affect the rate of growth of vegetation, as well as which vegetation types and species are present on the landscape.

Single-leaf pinyon pine has both increased in density and expanded its range since the early 1900's (Blackburn and Tueller 1970, Miller et al. 2008). It is difficult to precisely define the causes of this expansion and infilling, but recent and ongoing climate change, as well as changes in land use, atmospheric composition, and disturbance regimes (especially wildfire) may be factors. Fire suppression can lead to long-term ecosystem changes (Gruell 1999). When coupled with climate change (Tausch 1999a, Miller et al. 2008) and land use changes such as moving from a non-grazing to a grazing regime, the effects of fire suppression can be significant. Structure of Great Basin woodlands has changed since the suppression of fire following European settlement (Tausch 1999b), which, in turn will affect disturbance regimes. In pinyon-juniper woodlands of the Great Basin, fires of increasing severity are a result of increased stand density (Tausch 1999a, 1999b). However, in a study testing the pyroclimatic hypothesis as an explanation for the post-European settlement reduction in fire frequency, Biondi et al. (2011) found that the mean fire return interval had changed even without fire suppression.

The landscape patterns and stand structure of pinyon-juniper woodlands in the Great Basin are a result of the differing effects of disturbance processes. Historically, fire has restricted old-growth pinyon-juniper to sites with rocky, poor soil, because marginal site conditions prevent dense undergrowth from providing the fine fuels required for fire spread (Romme et al. 2009). Other disturbance agents such as insects or disease can persistently thin stands, or cause widespread mortality events, especially in combination with drought (Shaw et al. 2005, Greenwood and Weisberg 2008). The most important biologic pests acting on pinyon-juniper include pinyon ips (*Ips confusus* (LeConte)), twig beetles (*Pityophthorus* spp. and *Pityogenes* spp.), pitch moths (families *Pyralidae* and *Sesiidae*), black stain root disease (*Leptographium wageneri* (Kendrick) Wingfield), and pinyon dwarf mistletoe (*Arceuthobium divaricatum* Engelm.) (Shaw et al. 2005). Greenwood and Weisberg (2008) found that stand density was the most important structural attribute for occurrence of both pinyon ips and dwarf mistletoe. This relationship suggests a negative feedback that can act to maintain relatively low stand densities.

Previous work on wildfire history in the Great Basin indicates variability in driving forces of wildfires. Dilts, et al. (2009) showed an east-west gradient in wildfire occurrence related to a higher frequency of lightning strikes in the east. They also found lightning strike frequency to be the best predictor of wildfire occurrence. This differs from results reported by Knapp (1997) - that ignition frequency was a function of fine fuel loads - possibly because Knapp had analyzed grasslands and not forested areas. Biondi, et al. (2011) found that the post-European settlement reduction in wildfires in the Mt. Irish area of southeastern Nevada was best explained by climatic changes, and not fire suppression or changes in land use.

Succession is a long term process that describes the trajectory of vegetation change following a disturbance. In pinyon-juniper woodlands of the Great Basin the successional trajectory after a wildfire includes early establishment of non-tree species, with woody species becoming dominant in the late-successional stage (Koniak 1985). Brush species can act as nurse plants for coniferous species that eventually shade out the brush species and become dominant. Species with a large seed cache, or with high occurrence on adjacent unburned sites, have a higher probability of early establishment, and hence of site dominance into the midsuccession stage. When considering the dynamics of Great Basin ecosystems, one has to take into consideration all of these ecological factors and their interactions.

Because of the complexity of ecosystem processes, simulation modeling is a valuable tool for testing the different effects of varying parameters (Costanza 2004). Simulation models typically describe the initial state of a system, its responses to stochastic drivers over a given time period, and its future states that result from the responses (He 2008, He et al. 2008). A vegetation disturbance simulation model uses vegetation states and system controls and drivers, e.g. climate and disturbance information, to predict trajectories over a given time period. The basic method for producing and validating such a model is to run simulations in areas with documented disturbances, and compare the simulation results with the actual results of those disturbances. The model logic is then adjusted until the simulated end-states are similar to the actual post-disturbance states. Once adjusted, the model can be run for areas or times outside the calibration interval. Accuracy of results can be measured using metrics that include canopy density, fuel loads, and vegetation types. When compared to successional changes in the vegetation, disturbances are infrequent enough that model calibration can be difficult.

This research examines the interaction among species invasion, wildfire regime, and climate in the Great Basin using the SIMulating Patterns and Processes at Landscape scaLEs (SIMPPLLE) model. SIMPPLLE is a vegetation disturbance model designed for landscape management in forests and grasslands. It emphasizes realistic representation of ecological processes over precise predictions of what disturbance events will occur and how the various components of the landscape will change (Chew et al. 2004). SIMPPLLE uses disturbance history for the analysis area to determine probability of initiation of a disturbance event. Decisions on spread of the disturbance event use site specific spatial information such as wind direction, slope, and vegetation attributes of adjoining vegetation units. As a management tool SIMPPLLE is designed to perform simulations quickly and allow users to easily modify input parameters for assessing potential end-states.

2 Methods

2.1 Simulation Model

Version 3.1.19 (Prototype) of SIMPPLLE uses vegetation maps as input, and for each vegetation unit it calculates the probability of a given disturbance either initiating in, or spreading to, that unit based on the known disturbance history for that area as well as ecological knowledge. Also included in the calculation of disturbance probability is the recent climatic history of the vegetation unit. An individual simulation can provide one potential scenario, while multiple simulations provide a range of results, hence an average resulting set of conditions and insight into stochastic variability.

The primary model tool used to control the ecological processes of succession and vegetative response after a stochastically determined disturbance is “pathways”. Each pathway is specific to the respective processes, so there is a pathway for succession, a pathway for light severity fire, another for mixed severity fire, etc. Pathways can hold the vegetation in its current state or allow increases or decreases in the attributes. For instance, through pathways the user determines the rate increase for canopy height and canopy density for each vegetation type.

Fire logic consists of several steps. The probability of wildfire occurrence is calculated for the area by using the number of fires for a ten-year period divided by the total surface of interest. If a fire starts, the system employs two types of logic: fire type and fire spread. Fire types include fire classes of Light Severity Fire, Moderate Severity Fire, and Stand Replacing Fire. Determination of fire type requires fire resistance of the vegetation type, recent processes at work within the vegetation unit, and whether the climate is drier or wetter than normal. Determination of fire spread uses, vegetation type and density of adjacent units, topography, and likelihood of successful suppression. It can also make use of recent processes such as drought, or treatments, such as thinning or grazing. Regeneration logic can be used to include knowledge about species with large seed caches, or if a species grows in high density next to a burned site.

SIMPPLLE also includes an open-ended field for vegetation data called Ecological Stratification (ES). This user-created attribute allows specification of ecologically relevant criteria for any zone where the model is used. For instance, if soil type is a primary factor for determining vegetation within the zone, then the ES field can include soils. Process pathways within the model can be specific to the different ES values. Slope steepness, aspect, elevation, and slope position classes were concatenated for the ES field (Table 1). Slope position refers to the location of the pixel relative to the major ridge line forming the mountain range. If the pixel is in the lower third then it is assigned a slope position of "lower", if it is in the middle third it is assigned and position of "mid", and if it is in the upper third it is assigned a position of "upper."

The ES field was used for differentiating different successional pathways between sites that were more or less likely to experience expansion and infilling of pinyon-juniper. Vegetation units defined as *Xeric Mixed Sagebrush Shrubland*, *Big Sagebrush Shrubland or Steppe*, *Salt Desert Scrub*, or predominantly mountain mahogany, located less than 2000 meters above sea level, and including south facing aspects above 2000 meters, were determined to have a potential of eventually becoming pinyon-juniper stands (Bradley and Fleishman 2008). This was achieved by creating pathways specific to pixels with the appropriate ES attributes . The ES field was also used to determine which units become cheatgrass (*Bromus tectorum* L.) following a stand replacing fire. Sites located lower than 2000 meters elevation with south and west aspects, if burned with a stand replacing fire, were assumed to become dominated by cheatgrass.

Data inputs to the model included modern vegetation, historic climate and fire, and elevation. Each is described in more detail below. Vegetation data were obtained from the LANDFIRE dataset (http://www.landfire.gov) created by the United States Forest Service (USFS) for use in fire management and fuels mapping. LANDFIRE data consist of vegetation classifications, generated using remotely sensed records and a vegetation prediction model, which were then field validated (Rollins and Frame 2006). This dataset was chosen because it covers the entire Great Basin, which allows consistent inputs for modeling in any mountain range of interest, and effectively provided the basis for expanding the SIMPPLLE model to the entire Great Basin.

Vegetation attributes used in this study are vegetation type, canopy height and canopy density. LANDFIRE provides 30 classes for canopy height, 10 for each lifeform, and 10 classes for canopy density. I considered this level of classification to be too detailed for the purposes of this study, because increased complexity does not necessarily improve usefulness of a model (Starfield 1997). Attributes provided by LANDFIRE were therefore reclassified to facilitate their use in the SIMPPLLE model. Canopy density values provided by LANDFIRE were reclassified into four density classes that applied to all lifeforms (Table 3). Canopy height was reclassified into two size classes for the herbaceous lifeform, three size classes for the shrub life form, and four classes for the tree lifeform (Table 2). Mature pinyon is a relatively short conifer with average heights around 6 - 12 m (Zouhar 2001), while other tree species in the study areas, such as ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and white fir (*Abies concolor* (Gord.& Glend.) Lindl. ex Hildebr.) can reach taller heights (Biondi and Bradley submitted). This disparity in potential average canopy heights between pinyon-juniper and other conifers was taken into account so that the model could be applicable to different potential canopy heights for different vegetation types.

Two time periods were acquired for calibrating the model. The 1999 LANDFIRE data were obtained using remotely sensed and field validation (Rollins and Frame 2006). A second version of LANDFIRE was produced in 2008; these later data were assumed to show changes in vegetation attributes resulting from ecological processes, including disturbance events. LANDFIRE data have 30-m pixel size, which is appropriate for field calibration of model simulations. However, due to the relatively large size of the analysis areas (Table 8), a majority filter algorithm was used to reduce pixel size to 120 meters for model simulations.

Vegetation types provided by LANDFIRE were renamed to a tree species name that already existed in SIMPPLLE, e.g. LANDFIRE's *Great Basin Pinyon-Juniper Woodland* was reclassified to "PIMOF." Many of the species codes used in this study already existed in SIMPPLLE because of its previous application to the Colorado Plateau. Each pre-existing species code in SIMPPLLE had pathways associated with it and they were used as a starting point to build the simulation pathways.

2.2 Historic Data

Simulations of future ecological conditions depend on how climatic controls on vegetation will change. In other words, given a particular vegetation at a given site, will a potential future climate still support that type of vegetation at that site? For this question to be answered, the climatic envelope, or suitable climate space, for each vegetation type included in the model must be specified (Pearson et al. 2002, Pearson and Dawson 2003, Trivedi et al. 2008). A suitable climate space for each vegetation type was defined using Parameter-elevation Regressions on Independent Slopes Model (PRISM) data from the PRISM Climate Group (Oregon State University, http://prism.oregonstate.edu). PRISM data are interpolated from values observed at climate stations using an algorithm that accounts for elevation, rain shadows, inversions, and other topographic controls on climate. PRISM data include 30-year averages and observed values for total monthly precipitation (PPT), average monthly minimum temperature (TMIN), and average monthly maximum temperature (TMAX).

Defining the suitable climate space involved finding the upper and lower bounds for each variable (PPT, TMIN, and TMAX) for the geographic space occupied by each vegetation type. Temperature bounds were calculated using 30-year averages during 1971 - 2000. All PRISM grid cells containing at least one pixel of the vegetation of interest were included. Minimum and maximum values of the TMIN and TMAX attributes were retrieved from the selected PRISM cells. Precipitation was calculated using observed monthly values instead of 30-year averages, so that minima and maxima could be retrieved instead of average monthly values. The years used for PPT (1971 - 2000) were the same as for temperature, and the technique for selecting input PRISM cells was the same.

Probability of fire occurrence for any given vegetation unit was calculated using historic information acquired from the National Fire Occurrence database available from the USDA Forest Service (http://www.fs.fed.us/fire/fuelman/fireloc.htm). This database includes fire records from federal lands for the eleven year period from 1986 to 1996. Data attributes include location, start date, containment date, fire size, and cause of ignition. Number of fires per fire size class are entered into the model through the user interface (Figure 1). Digital Elevation Model (DEM) data are from the National Elevation Dataset, available from the USGS (http://ned.usgs.gov/). These data, which are at 10-m spacing and cover the entire US, were resampled using a nearest neighbor algorithm to match the 120-m resolution of the vegetation data. For the Ecological Stratification field, elevation data were used to calculate slope steepness, aspect, and slope position. Elevation data were also used to compare position of adjacent vegetation units to calculate probability of fire spread. Units that adjoin and are higher than a burning unit are considered more likely to experience spread than a unit that is lower than the adjacent unit.

2.3 Sites

The hydrologic Great Basin (Figure 2) is approximately 50 million hectares in size. It is comprised of basin and range topography, with north-south trending mountain ranges. There are no outlets to the ocean for surface flow of water (Grayson 1993). The Great Basin has cold, snowy winters and hot, dry summers as indicated by examination of the PRISM dataset. While the hydrologic Great Basin contains parts of three North American deserts - the Sonora, Mojave, and the Great Basin - the majority of its vegetation is typical of the Great Basin Desert.(Trimble 1999) Valley vegetation consists largely of shrubs and grasses, and the mountain ranges have a variety of coniferous species, primarily single-leaf pinyon pine (Trimble 1999).

Three mountain areas were used for this study: Clover Mountains, Sheep Range, and Snake Range (Figure 3). The Clover Mountain study site is in southeast Nevada and it ranges from 1013 m to 2270 m above mean sea level. Total annual precipitation (PPT) within the study site ranges from an average of 260 mm at the lower elevations to a mean of 510 mm at the higher elevations. Average annual minimum temperature can be as low as -7° C; average annual maximum temperature can be as high as 37° C (Table 4). Clover Mtn. had 35 ES classes (Table 5), and vegetation, according to the LANDFIRE dataset, is 85% *Great Basin Pinyon-Juniper Woodland*, 8% *Coleogyne ramosissima Shrubland Alliance*, 3% *Mojave Mid-Elevation Mixed Desert Scrub* (Table 6), with the remaining 4% consisting of 23 different vegetation and land cover types (Table S1). *Great Basin Pinyon-Juniper Woodland* is described as consisting of either pure *Pinus monophylla* (pinyon), pure *Juniperus osteosperma* (Torr.) Little., or a mix of the two, and occurs in dry mountain ranges of the Great Basin, typically at elevations ranging from 1600 to 2600 m (NatureServe 2010). *Coleogyne ramosissima Shrubland Alliance* is dominated or co-dominated by blackbrush (*Coleogyne ramosissima* Torr.). *Mojave Mid-Elevation Mixed Desert Scrub* can also be co-dominated by blackbrush. Both are transitional vegetation types between the Mojave and Great Basin deserts. The primary difference between the two is the lack of *Yucca* *brevifolia* Englm. in the former (NatureServe 2010). The largest canopy cover class is the 20% to 40% coverage spread over 46% of the landscape (Table 7), with 85% of the area covered by a tree lifeform (Table 8).

The Sheep Range study site is located further south (Figure 3) , and ranges from 1667 m to 3017 m above mean sea level. Total annual precipitation (PPT) at the study site ranges on average from 205 mm at the lower elevations to 424 mm at the higher ones. Average annual minimum temperature can be as low as -10° C; average annual maximum temperature can be as high as 33° C (Table 4). The Sheep Range had 45 ES classes (Table 5). Vegetation, according to the LANDFIRE dataset, is 49% *Great Basin Pinyon-Juniper Woodland*, 30% *Mojave Mid-Elevation Mixed Desert Scrub*, 12% *Southern Rocky Mountain Ponderosa Pine Woodland* (Table 6), with the remaining 9% consisting of 12 different vegetation and land cover types (Table S2). *Southern Rocky Mountain Ponderosa Pine Woodland* is widespread throughout western U.S. mountainous areas, is always dominated by ponderosa pine, though other coniferous species may be present, and can occur at elevations ranging from 1980 - 2800 m (NatureServe 2010).

The Snake Range study site is the easternmost one, and. it ranges from 1733 m to 3978 m above mean sea level. Total annual precipitation (PPT) varies on average from 247 mm at the lower elevations to 859 mm at the higher elevations. Average annual minimum temperature can be as low as -8° C; average annual maximum temperature can be as high as 32° C (Table 4). The Snake Range had 32 ES classes (Table 5), and vegetation, according to the LANDFIRE dataset, is 45% *Great Basin Pinyon-Juniper Woodland*, 20% *Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland*, 10% *Great Basin Xeric Mixed Sagebrush Shrubland* (Table 6), with the remaining 24% consisting of 25 different vegetation and land cover types (Table S3). *Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland* is a mountain mahogany dominated shrubland or woodland that typically occurs from 600 to 2650 m in mountain ranges throughout the intermountain western U.S. (NatureServe 2010). *Great Basin*

Xeric Mixed Sagebrush Shrubland is dominated by *Artemisia nova* A. Nelson, or *Artemisia arbuscula* Nutt., and may be co-dominated by *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young or *Chrysothamnus viscidiflorus* (Hook.) Nutt. This vegetation type occurs on a variety of topographies at elevations ranging from 1000 to 2600 m (NatureServe 2010).

2.4 Model Calibration

Models are intended to predict for unknown areas or times, or for non-existent conditions, and must be tested by comparing results of simulations for known areas and times to actual conditions. This process is known as model calibration (Caswell 1976, Oreskes et al. 1994). For this study, predictions of the SIMPPLLE model were validated by running a simulation for a given time period in the Snake Range, and compare the predicted results to ground-truth vegetation data collected in the field. The west side of the Snake Range was chosen because of road access to terrain with varying elevation and aspect (Figure 4). The field calibration area also had to contain proportions of vegetation types similar those found throughout the study areas, which meant that the calibration area had to be predominately pinyon-juniper with components of mountain mahogany and montane mixed coniferous forest. The field calibration area consisted of 78% *Great Basin Pinyon-Juniper Woodland*, 10% *Abies concolor Forest Alliance*, and 6% *Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland*, 5% *Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland* with the remaining 1% belonging to nine different vegetation types (Table S4), according to the 2008 LANDFIRE dataset.

After the calibration area was chosen, 20 plot locations were randomly generated. Vegetation data was collected at these locations over a 30 by 30 m area because the height of all individuals in the dominant canopy type had to be measured. Vegetation types of these 20 plots in the 2008 LANDFIRE dataset were 75% *Great Basin Pinyon-Juniper Woodland*, 15% *Abies* *concolor Forest Alliance*, and 10% *Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland* (Table S5). Data collected at the sample plots included vegetation type, average canopy height, and canopy cover density. Visual inspection was used to decide which LANDFIRE vegetation class the pixels would fall in. Average canopy height was calculated by measuring the height of all individual plants in the dominant vegetation and then placing the average height in one of the canopy height classes described above. For instance if the dominant vegetation was assessed as being pinyon-juniper, then heights of each individual pinyon and juniper would be measured. Canopy density was calculated using the transect method: three transects were measured for the length of the 30 m pixel in the north/south direction at 10 m intervals, with five meters from either east/west side of the pixel (Figure 5). The distance of ground covered as if viewed from above was measured, and the percent of coverage was calculated to obtain the canopy density class.

These field collected data were then compared to predicted data from a simulation run for the entire Snake Range analysis area. Modeled data from 1999 were used for 100 10-year runs. Field data were compared to the vegetation type, height and densities with the highest probability of occurrence from the 100 10-year simulations. The comparison method used was confusion matrices (Congalton 1991), so named because they illustrate where the model is confusing one state for another. Simulation results were examined by comparing SIMPPLLE simulated data with the LANDFIRE 2008 data. The simulations were initialized with LANDFIRE data from 1999. 100 runs of 10 years duration were performed, and vegetation states with the highest probability were considered to be the end state.

2.5 Climate Projections

A single 100-year simulation was performed for the Snake Range analysis area. Data from GCM projections are used to run climatically sensitive simulations into the future. The predicted future climate states were acquired from the A2 climate scenario of the Intergovernmental Panel on Climate Change (IPCC 2007). The IPCC was formed by the World Meteorological Organization and the United Nations Environment Programme to evaluate potential risks of anthropogenic climate change. The IPCC has created a variety of emissions scenarios to be used in GCMs by providing estimates of greenhouse gases under an array of different future conditions. This model utilized the scenarios available for GCM runs offered by the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (2007). Global climate models are produced at a global extent with a resolution that is too large to be of use for subregional purposes such as this study (Figure 6). Bias Corrected and Spatially Disaggregated (BCSD) climate data based on GCM projections are available from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/, a multi-organization effort providing downscaled data appropriate for use at a regional or subregional scale. The GCM data are regridded to a higher resolution, and then a quantile mapping procedure is applied to compare the GCM projections with observed data for an overlap time period. Biases in the GCM data can then be corrected for each grid cell. A more detailed explanation of the BCSD process is available in Bureau of Reclamation (2013) and Maurer *et al.* (2007).

The Hadley Centre Coupled Model, version 3 (HadCM3) was used for the model projections in this study. HadCM3 was produced by the Hadley Centre For Climate Research. The IPCC emissions scenario used was A2, which estimates greenhouse gas emissions based on a fragmented global future that preserves local identities and advocates self-reliance. This scenario is a higher emissions path (when compared to other emission scenarios) that is characterized by slow technological and economic change, while global population rates continually increase (IPCC 2007, WCRP 2007). Temperature and precipitation projections can be loaded into SIMPPLLE to assess effects of potential climate change on a given area. For instance, if projected climate exceeds suitable bounds for a given vegetation type in a given area that vegetation will not regenerate after disturbance.

3 Results

The 100 simulations provided probabilities of occurrence for vegetation type, density or canopy height, and those with the highest probability were used for comparison with field data. The model was most accurate at predicting vegetation type: 14 of 20 pixels agreed with field observations (Table 9), providing an overall accuracy of 70%. The model performance was lower for size class and canopy density, with 11 and 8 out of 20 (Tables 10 & 11), providing overall accuracies of 55% and 40%, respectively. Predictions of vegetation type generally had fewer "producer's errors" (Table 12), which is calculated by dividing the correctly predicted number of pixels for a particular attribute by the number of pixels in the ground-truth data that actually had that attribute. "User's error" is calculated by dividing the correctly predicted number of pixels for a particular attribute by the total number predicted for that attribute.

There were differences between the simulated end states in 2008 and the LANDFIRE 2008 data. Some differences were consistent between the three study sites, others were site specific, possibly indicating a combination of model logic, discrepancies between simulated processes and real ones, and/or dissimilar LANDFIRE production of the 2008 data compared to the 1999 data. Simulated vegetation types matched the 2008 data for the three analysis areas (Tables 13, 14 & 15), but simulated size classes differed from the LANDFIRE 2008 data in the three areas (Tables 16a & 16b). Simulated cover density classes were similar to the LANDFIRE 2008 data only in the Clover Mts. (Tables 16a & 16c).

Simulations performed for the Clover Mtn. analysis area compared well with the LANDFIRE 2008 data, except for shrub sizes (Table 16b). Simulations showed a decrease in overall shrub cover from 1999 to 2008, as did the 2008 LANDFIRE data, which however indicated more cover in the 0 - 0.5 m shrub size than what was predicted. Simulation results for the Sheep Range differed from the 2008 LANDFIRE data in cover and size classes for the tree lifeform, but not for shrub or herbaceous ones (Table 16b). For cover classes, 2008 data showed an increase in the >= 20 and < 40% class and a decrease in the >= 40 and < 70% class, while the simulated data showed no change in any of the classes (Table 16c). Simulation results for the Snake Range departed from the 2008 LANDFIRE data more than in the other two study areas. Predicted size classes differed considerably for both tree and shrub lifeforms, and predicted cover differed considerably in three classes (Table 16c). Simulated cover classes changed little over time, whereas the 2008 data showed considerable changes. According to LANDFIRE, in 2008 almost 70% of the landscape was occupied by the >= 20 and < 40% cover class, while the simulated data pointed to almost 40% (Table 16c).

End states of the 100-year simulation using the IPCC scenario were very different from the initiation data. Simulated size classes suggested that about 72% of the landscape would become covered by the tree life form in a canopy height class of 10 to 25 meters, with 9% of the remaining landscape becoming herbaceous (Table 17). Ending state for cover classes showed an overall increase in the denser cover classes. The >= 40 and < 70% cover class, which initialized at 0.3% of the landscape, ended the simulation at 76.5% of the landscape. Long term trends of disturbance events over the 100-year simulation showed a slight increase in annual acreage burned.

4 Discussion

The newly created Great Basin Zone for the SIMPPLLE model was adequate at predicting vegetation type, yet improvement is needed for predicting vegetation canopy density and height. There are three components of model validation: parameterization, input data, and calibration data. Parameterization includes vegetative pathways, which determine pace and trajectory of ecological succession considering disturbances, and fire history, which determines probability and severity of fire disturbances. Assessing the accuracy of the input, or initialization, data is well beyond the scope of this research. The input data are simply the initial conditions that are used in the simulation whether or not they accurately describe reality. However, if the model is initialized with unrealistic canopy heights or densities, simulated end states will not be accurate. For example, the model parameters restrict 0 - 5 m tree canopy height to a density of < 70% for PIMOF, although input data from 1999 have densities higher than this, so the densities must be reduced through the first transition step, or the data have to be altered prior to use by reducing all densities of > 70% to the next lowest density class.

Multiple changes occurred between 1999 and 2008 according to LANDFIRE data. Looking first at vegetation cover classes, the areas with 40 ≤ cover < 70% at the Clover Mtn. declined from 25 to 9% of the landscape while the next lower category, 20 ≤ cover < 40%, expanded from 46 to 70% (Tables 7 & 16c). The most likely reason for reduced extent of the high-cover class was the Meadow Valley fire in 2005, which burned within the Clover Mtn. area (Bauer et al. 2011). The Sheep Range experienced a fire in 2004, the Coyote Springs fire, which could explain the reduction in 40 ≤ cover < 70% from 27% in 1999 to 10% in 2008 (Tables 7 & 16c). In the Snake Range the area with 40 ≤ cover < 70% decreased from 38% in 1999 (Table 7) to 19% in 2008 (Table 16c) despite the lack of recorded fires, and the next lower category, 20 ≤ cover < 40%, increased from 40% to 69%. Possible explanations include either mortality due to drought and/or insect outbreaks, issues in the LANDFIRE data from 1999 to 2008, or some combination of the two.

At the Clover Mts. shrub and tree size classes experienced an 11% reduction, while the herbaceous size class of CLOSED-HERB increased by the same amount, from 0 to 11%. This could be a result of shrub and tree areas burning in the Meadow Valley fire, then becoming occupied by the herbaceous life form. In the Sheep Range shrub areas did not change much between 1999 and 2008, and the tree lifeform grew into larger size classes. For pinyon-juniper, the 0-5 m size class decreased from 31% to about 5% of the landscape. In the Snake Range, shrub lifeforms increased in size, while tree lifeforms increased less because of slower growth of pinyon-juniper species.

Simulated vegetation types matched the 2008 LANDFIRE data, which is to be expected because there are relatively few situations where vegetation type will change during a ten-year period. In some ecological groups a stand-replacing fire can bring vegetation type to cheatgrass (BRTE), and late successional shrub types can transition to pinyon-juniper, but otherwise succession leads to a maximum static height and density. Succession allows density and size class to increase, while disturbance usually reduces or keeps constant these attributes, as well as canopy height, over time. In the Clover Mts. vegetation became denser, as indicated by greater areas with 40 ≤ density < 70% (Table 16c). In the Sheep Range neither density nor size class changed at all over the landscape. It is possible that succession was set to move too slowly to progress in a ten-year simulation. Predicted 2008 density in the Snake Range was quite similar to the 1999 input, presumably because of slow growth rates of the widespread pinyon-juniper vegetation. When the predicted and reported 2008 data are compared, large differences emerge, but this may be due to a change in how LANDFIRE data were generated in 1999 and 2008, hence the change is not in the vegetation, and rather in the representation of the vegetation.

At Clover Mtn. the simulation predicted the same percent of landscape to convert to herbaceous lifeform as was found in the 2008 LANDFIRE data. The 2008 data showed the result of the Meadow Valley fire with much of the previous shrub vegetation converting to herbaceous cover. This is what was simulated by the SIMPPLLE model, but there were multiple, small, stand-replacing fires that converted vegetation in different portions of the analysis area. Of the 2381 pixels that were TALL-FORB in the simulated 2008 data only 155 were also TALL-FORB in the 2008 LANDFIRE data. The majority of the simulated TALL-FORB pixels, 1866, were initialized as pinyon-juniper, and remained pinyon-juniper in the 2008 LANDFIRE data. Of the 2396 pixels that were attributed as TALL-FORB in the 2008 data the majority, 1424, initialized as *Mojave Mid-Elevation Mixed Desert Scrub* or *Coleogyne ramosissima Shrubland Alliance*, which use the species code CORA in the SIMPPLLE model. The 2008 LANDFIRE data reflected the result of a fire burning CORA pixels, which subsequently came back as herbaceous, while the model simulated pixels as converting to BRTE after a stand replacing fire. In this case the model did extremely well in predicting overall vegetation trajectories.

If we are to assume the initialization and calibration data are correct, then improving height and density predictions would simply be a matter of adjusting the temporal rate of succession. For both the Clover Mtn. and Snake Range, simulated succession moved more quickly for shrubs than the 2008 data would indicate. For the Clover Mts., both 2008 LANDFIRE data and simulated data showed a decrease in overall shrub cover compared to 1999, but the 2008 data indicated more cover would be in the 0 - 0.5 m shrub size than what was predicted by the simulation (Table 16b). The 2008 LANDFIRE data for the Snake Range showed little change in percent of landscape for shrub size classes, and again the simulated 0-0.5 m shrub size grew into the 0.5-1.0 m shrub size class too quickly.

The model used in this study requires spatially explicit vegetation maps and the time span between initialization data (1999) and calibration data (2008) is on the low end of acceptable time ranges for this model. The model can run at yearly increments but the slow growth rates of common species, such as pinyon, and infrequency of disturbance events makes longer time spans preferable. It is difficult to assess the model accuracy of predicting likelihood of fire events and their severity when the calibration simulations include $\leq$ 10 years. While fires are not rare in the mountain ranges of the Great Basin, given the relatively small analysis areas, and the temporal constraints of 10-year simulations, the probability of having a fire event is low. In pinyon-juniper stands, as trees become the dominant lifeform and density increases, the likelihood of moderate fires is reduced while that of infrequent high-severity fires increases (Miller et al. 2008).

Expansion of pinyon-juniper has historically been more likely on sites below 2000 meters above mean sea level, and on south facing aspects above 2000 meters (Bradley and Fleishman 2008); Weisberg, *et al.* (2007). There were four vegetation types that typically bounded the pinyon-juniper vegetation type in the LANDFIRE data; *Inter-Mountain Basins Mixed Salt Desert Scrub* (ATCO-ARBI3), *Great Basin Xeric Mixed Sagebrush Shrubland* (ARAR), *Inter-Mountain Basins Big Sagebrush Shrubland* (ARTR2), and *Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland* (CELE). These four vegetation types were allowed in the model to eventually convert to pinyon-juniper if the site was below 2000 meters, or above 2000 meters if it was south facing. Before converting to the pinyon-juniper vegetation type, individual pixels must reach their maximum allowed height and density. In our simulations very little conversion to pinyon-juniper occurred because there were few areas with advanced height and density classes that could change vegetation type within a 10-year simulation. A component of pinyon-juniper expansion is infilling, or increasing density, of existing woodland. The 10-year simulations are too short for much density increase, but the 100-year simulation showed an overall increase of high-density pinyon-juniper areas, as well as expansion of the total pinyon-juniper area by 11,578 ha (Table 18). The majority of that was lower-elevation sagebrush shrub that converted to pinyon-juniper.

End states of the 100-year simulation were considerably different from the initiation data, likely because of long-term successional processes and the influence of low-severity fires. Pixels that began and ended the simulation as shrub lifeform were typically reset to the 0-0.5 m shrub class through burning, and were located in aspect/elevation classes that would not convert them to cheatgrass. Of all the areas that began the simulation as shrub life form, 86% became tree lifeform (Table 19), primarily through successional processes and continued expansion of pinyon-juniper woodland.

5 Conclusion

Landscape simulation models are a valuable method for predicting potential vegetation states and the effects of disturbance on ecosystems. The SIMPPLLE model is especially helpful for capturing expert ecological knowledge. The Great Basin zone variant of this simulation model was constructed so that pathways, fire regime, and ecological knowledge were built into it for three mountain areas: the Snake Range, the Sheep Range, and the Clover Mts. For the Snake Range we also incorporated climate information through suitable climate spaces that were developed for the most prevalent vegetation types. Simulation then used downscaled IPCC A2 climate predictions to obtain 100-year predictions of vegetation in that area. In terms of model calibration with LANDFIRE data, we found that the model performed better for shrub than for tree lifeform states.

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7 Figures

Figure 1: Fire occurrence data input user interface.

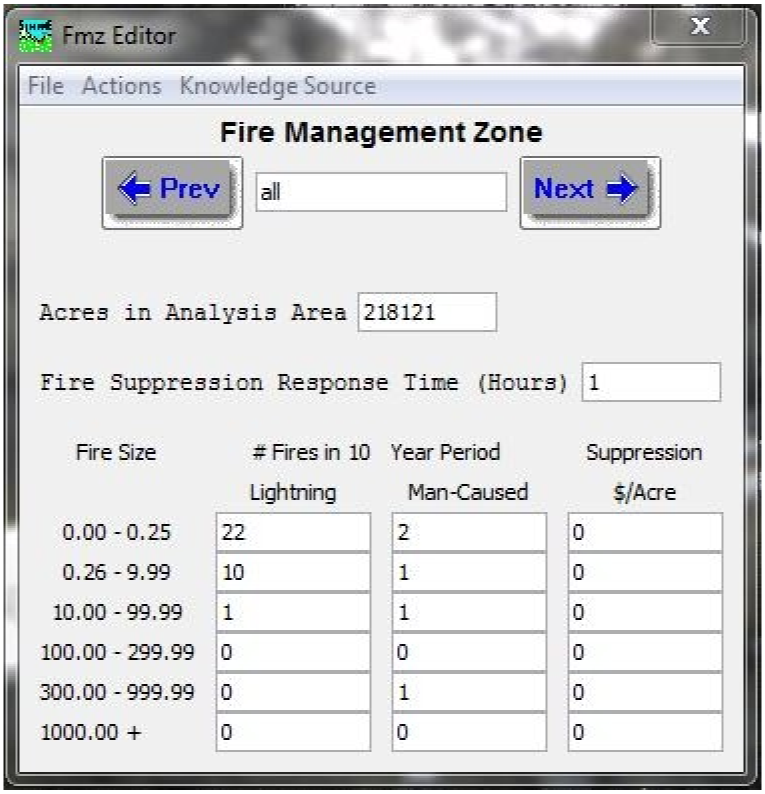


Figure 2. Hydrologic Great Basin.

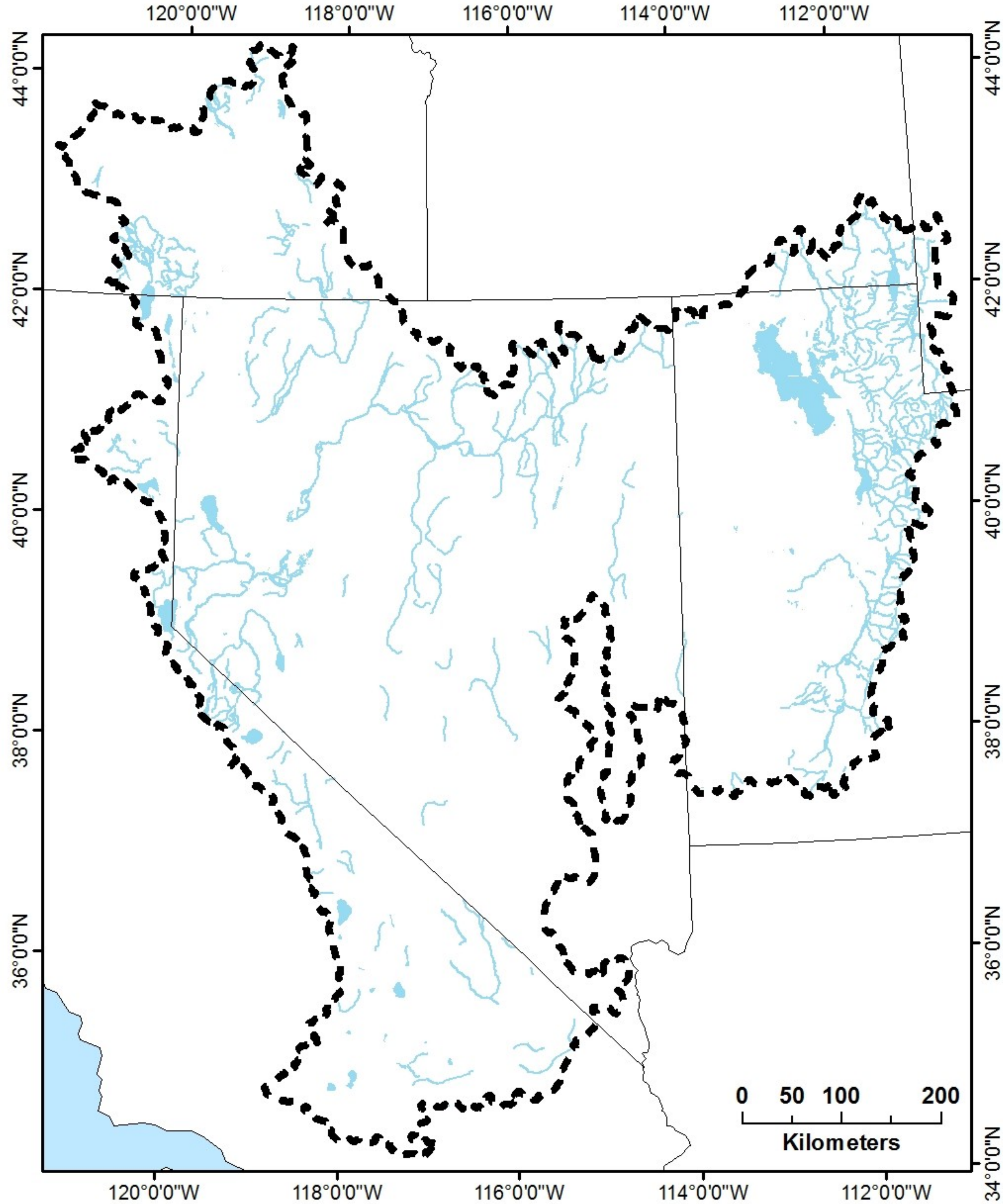


Figure 3. Map of study site locations.

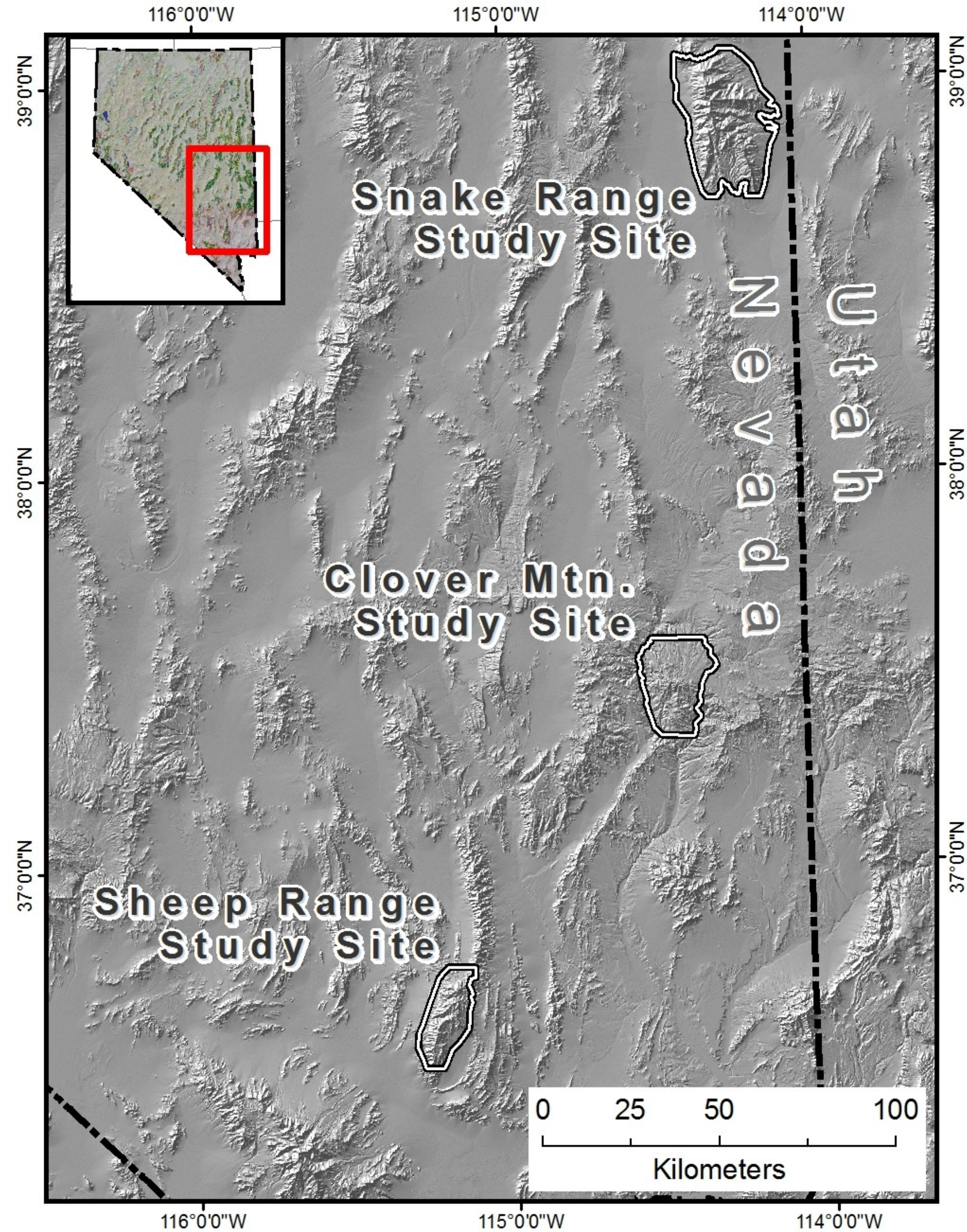


Figure 4: Map of field validation sites in the Snake Range.

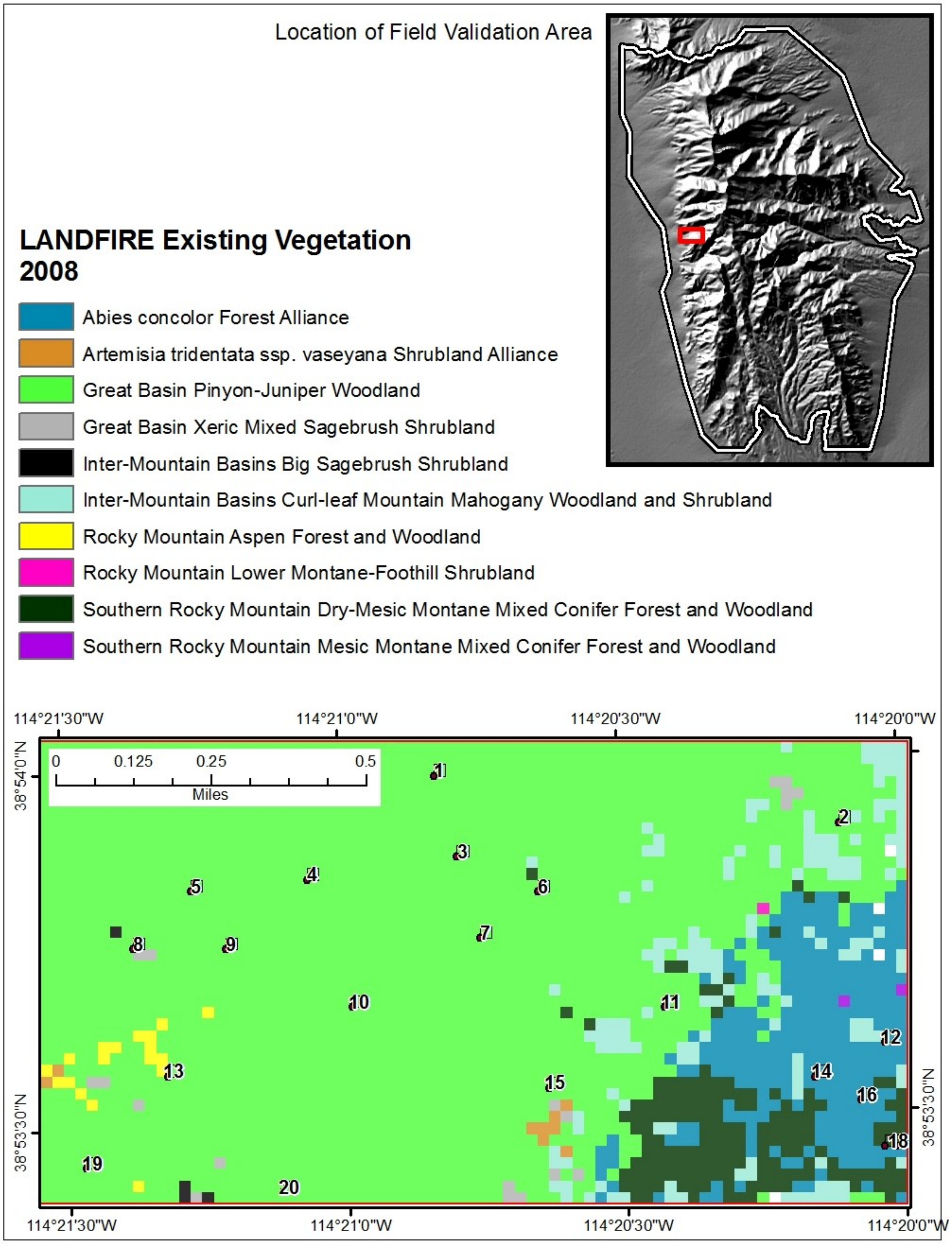


Figure 5: Graphic showing transect layout for measuring canopy density.

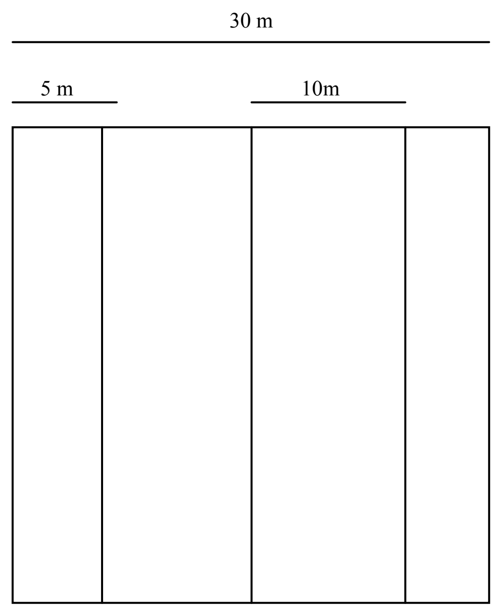
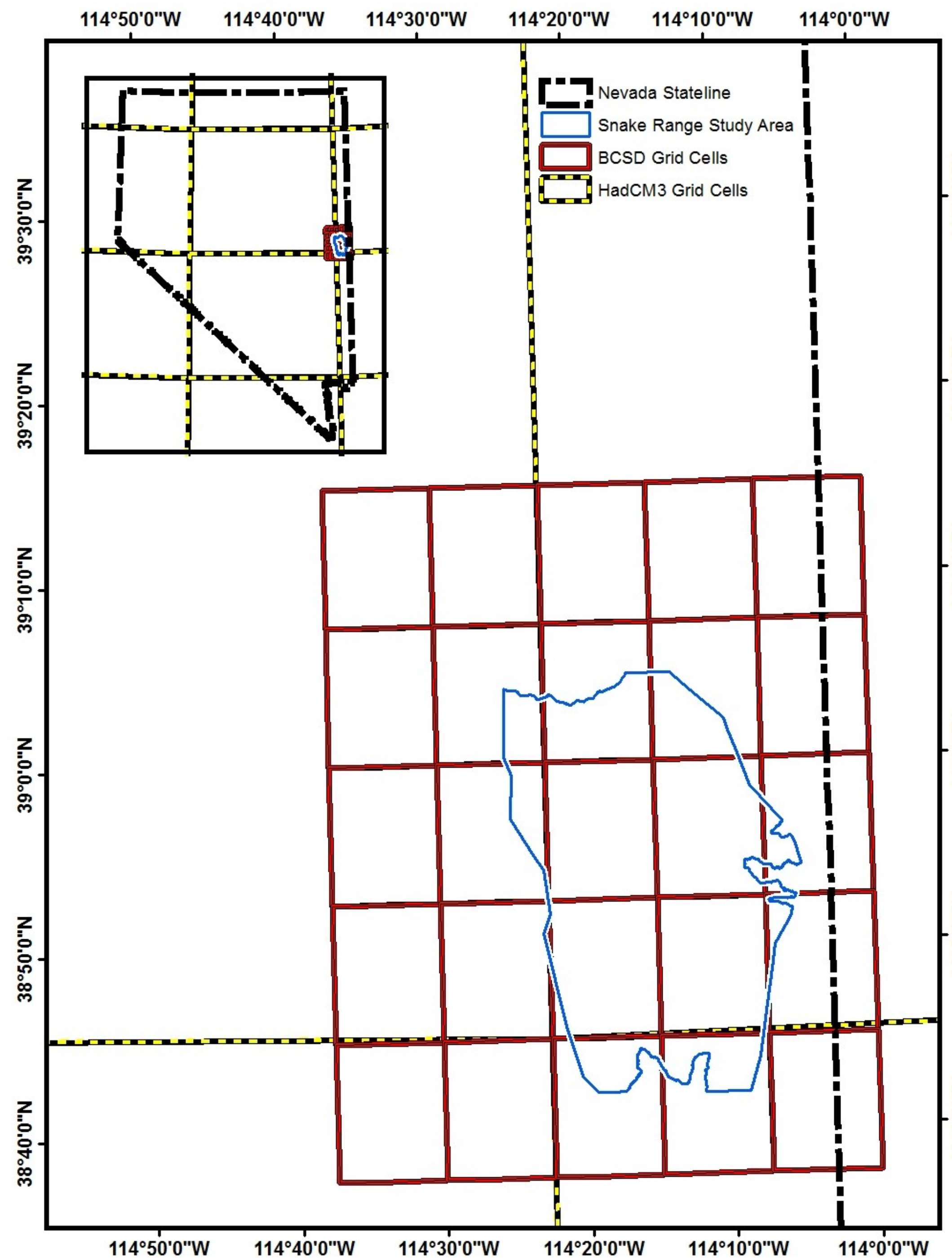


Figure 6: Map of BCSD grid cells that overlap the Snake Range study area.



8 Tables

Table 1: Parameter categories for the Ecological Stratification field.

Aspect	Slope (degrees)	Elevation (meters)	Slope position
N	0-22.5	500-1000	lower
S	22.6-45	1000-2000	mid
E	>45	2000-3500	upper
W			

Table 2: Size classes for vegetation data.

	Size Class
Herbs	OPEN-HERB
	CLOSED-HERB
Shrubs	0 - 0.5 m
	0.5 m - 1.0 m
	>1.0 m
Trees	0 - 5 m
	5 m - 10 m
	10 m - 25 m
	>25 m

Heights in Meters

Table 3: Density classes for all lifeform types.

Density Classes
>= 10 and < 20%
>= 20 and < 40%
>= 40 and < 70%
>= 70 and <= 100%

Table 4: Climate statistics for the three study areas derived from PRISM climate averages for 1971 to 2000.

	Clover Mtn.	Sheep Range	Snake Range
Average Annual Precipitation (mm)	260 - 510	205 - 424	247 - 859
Temperature Range (C)	-7° - 37°	-10° - 33°	-8° - 32°

Table 5: Number of Ecological Stratification classes for each study area.

	ES Classes
Clover Mtn.	35
Sheep Range	45
Snake Range	32

Table 6: Three most abundant LANDFIRE vegetation types for each study area.

	LANDFIRE Vegetation Name	Species Code	Hectares
Clover Mtns	Great Basin Pinyon-Juniper Woodland	PIMOF	37839
	Coleogyne ramosissima Shrubland Alliance	CORA	3650
	Mojave Mid-Elevation Mixed Desert Scrub	CORA	1202
Sheep Range	Great Basin Pinyon-Juniper Woodland	PIMOF	14639
	Mojave Mid-Elevation Mixed Desert Scrub	CORA	9068
	Southern Rocky Mountain Ponderosa Pine Woodland	PIPO	3537
Snake Range	Great Basin Pinyon-Juniper Woodland	PIMOF	39960
	Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland	CELE	17369
	Great Basin Xeric Mixed Sagebrush Shrubland	ARAR	8994

Table 7: Percent of landscape of canopy cover class of initialization data for three study areas.

	Clover Mtn		**Sheep Range**		**Snake Range**	
Cover Class	Hectares	Percent of Landscape	Hectares	Percent of Landscape	Hectares	Percent of Landscape
>= 10 and < 20%	12256	27.4	6697	22.3	14128	16
>= 20 and < 40%	20619	46	12776	42.5	34874	39.5
>= 40 and < 70%	11343	25.3	8202	27.3	33178	37.6
>= 70 and <= 100%	393	0.9	2389	7.9	2596	2.9

Table 8: Percent of landscape of size class of initialization data for the three study areas.

	Clover Mtn		**Sheep Range**		**Snake Range**	
Size Classes	Hectares	Percent of Landscape	Hectares	Percent of Landscape	Hectares	Percent of Landscape
0 - 0.5 m	4349	9.7	6746	22.4	13383	15.2
0.5 m - 1.0 m	876	2	809	2.7	344	0.4
>1.0 m	1276	2.8	3090	10.3	154	0.2
0 - 5 m	36580	81.7	9472	31.5	47241	53.5
5 m - 10 m	1488	3.3	3977	13.2	17309	19.6
10 m - 25 m	19	0	5897	19.6	6340	7.2
OPEN-HERB	4	0	0	0	0	0
CLOSED-HERB	20	0	72	0.2	4	0
Totals	44612	99.5	30063	99.9	84775	96.1

Table 9: Confusion matrix for vegetation type for the field validation area within the Snake Range. Vegetation types referenced by species codes can be found in Table S3.

		Vegetation Type Predicted					
		ABCOC	PSME-PIPO	CELE	PIMOF	ARAR	
Actual	ABCOC	3	2				5
	PSME-PIPO						0
	CELE				3		3
	PIMOF				11		11
	ARAR				1		1
		3	2	0	15	0	20

Table 10: Confusion matrix for size class for the field validation area within the Snake Range.

		Size Class Predicted					
		0.5 m - 1.0 m	>1.0 m	0 - 5 m	5 m - 10 m	10 m - 25 m	
Actual	0.5 m - 1.0 m			1			1
	>1.0 m			1			1
	0 - 5 m			9			9
	5 m - 10 m			3	2		5
	10 m - 25 m				4		4
		0	0	14	6	0	20

Table 11: Confusion matrix for density class for the field validation area within the Snake Range.

		Canopy Density Predicted				
		>= 10 and < 20%	>= 20 and < 40%	>= 40 and < 70%	>= 70 and <= 100%	
Actual	>= 10 and < 20%		1	3		4
	>= 20 and < 40%		3	6		9
	>= 40 and < 70%		2	5		7
	>= 70 and <= 100%					0
		0	6	14	0	20

Table 12: Errors of omission and commission for confusion matrices.

		Producer's Accuracy	**User's Accuracy**
Vegetation Type	ABCOC	60%	100%
	PSME-PIPO	0%	0%
	CELE	0%	0%
	PIMOF	100%	73%
	ARAR	0%	0%
Size Class	0.5 m - 1.0 m	0%	0%
	>1.0 m	0%	0%
	0 - 5 m	100%	64%
	5 m - 10 m	40%	33%
	10 m - 25 m	0%	0%
Density Class	>= 10 and < 20%	0%	0%
	>= 20 and < 40%	33%	50%
	>= 40 and < 70%	71%	36%
	>= 70 and <= 100%	0%	0%

Table 13: Simulated and comparison vegetation type for Clover Mtn. study area.

Vegetation Type	Clover Mtn 2008 Data Hectares	Clover Mtn 2008 Data Percent of Landscape	Clover Mtn Simulation Data Hectares	Clover Mtn Simulation Data Percent of Landscape
PIMOF	34685	77.2	34649	77.3
TALL-FORB	3440	7.7	3427	7.7
CORA	2364	5.3	2278	5.1
ACHY	1375	3.1	1375	3.1
ARAR	887	2	887	2
POFR	524	1.2	524	1.2
ARTR2	492	1.1	492	1.1
QUTU	425	0.9	425	0.9
RIP	245	0.5	242	0.5
AGR	137	0.3	137	0.3
BA	130	0.3	130	0.3
QUGA	82	0.2	82	0.2
CELE	72	0.2	72	0.2
ATCO-ARBI3	55	0.1	55	0.1
POTR5	16	0	16	0
DEV-FOR	3	0	3	0
WATER	1	0	1	0

Table 14: Simulated and comparison vegetation type for Sheep Range study area.

Vegetation Type	Sheep Range 2008 Data Hectares	Sheep Range 2008 Data Percent of Landscape	Sheep Range Simulated Data Hectares	Sheep Range Simulated Data Percent of Landscape
PIMOF	14688	48.5	14639	48.7
CORA	9315	30.7	9068	30.2
PIPO	7112	23.4	7146	23.8
ARAR	1187	3.9	1223	4.1
ABCOC	913	3	897	3
ARTR2	321	1.1	325	1.1
PIAR	203	0.7	202	0.7
TALL-FORB	124	0.4	144	0.6
QUTU	52	0.2	30	0.1
POFR	35	0.1	33	0.1
BA	4	0	8	0
RIP	1	0	3	0

Table 15: Simulated and comparison vegetation type for Snake Range study area.

Vegetation Type	Snake Range 2008 Data Hectares	Snake Range 2008 Data Percent of Landscape	Snake Range Simulated Data Hectares	Snake Range Simulated Data Percent of Landscape
PIMOF	40370	45.7	39960	45.3
CELE	17431	19.7	17454	19.8
ARAR	8927	10.1	8994	10.2
PIEN-ABLA	4831	5.5	4692	5.3
ARTR2	3931	4.5	3941	4.5
BA	2936	3.3	3447	3.9
POTR5	2432	2.8	2399	2.7
PSME-PIPO	2369	2.7	2369	2.7
ABCOC	2131	2.4	2118	2.4
PIAR	1398	1.6	1380	1.6
ATCO-ARBI3	852	1	852	1
POTR5-PSME-PIEN-ABLA	517	0.6	514	0.6
AGR	71	0.1	14	0
POFR	60	0.1	89	0.1
SNOW-ICE	53	0.1	43	0
TALL-FORB	10	0	4	0
QUGA	7	0	7	0
NF	1	0	49	0.1

Table 16a: Legend describing symbols used to explain differences in percents of landscape between simulated states and 2008 LANDFIRE data. If the difference between simulated data and LANDFIRE data was less than or equal to 2% then the difference is symbolized with an equals sign. If the difference is greater than 2% and less than or equal to 10% it is symbolized with a single arrow. The arrow will point up if the simulated data are over-predicted, and down if under-predicted. If the difference is greater than 10% it is symbolized with two arrows.

Difference between percents of landscapes	Symbol
<= 2%	=
> 2% <=10%	⬆
>10%	⬆ ⬆

Table 16b: Comparison of differences in percents of landscape between simulated size class states and 2008 LANDFIRE data for all study areas.

	Snake Range	Clover Mtn.	Sheep Range
0 - 0.5 m	↓	↓	=
0.5 m - 1.0 m	↑	↑	=
>1.0 m	=	=	=
0 - 5 m	↑↑	=	↑↑
5 m - 10 m	↓↓	=	↓↓
10 m - 25 m	↓	NA	=
OPEN-HERB	NA	=	NA
CLOSED-HERB	=	=	=

Table 16c: Comparison of differences in percents of landscape between simulated density class states and 2008 LANDFIRE data for all study areas.

	Cover		
	Snake Range	Clover Mtn.	Sheep Range
>= 10 and < 20%	↑	=	=
>= 20 and < 40%	↓↓	↓↓	↓↓
>= 40 and < 70%	↑↑	↑↑	↑↑
>= 70 and <= 100%	=	=	↓

Table 17: Percent of landscape for size classes for initiation and simulation data for 100 year simulation using A2 scenario.

	Snake Range Initiation Data		Snake Range 100-year Simulation Data	
Size Classes	Hectares	Percent of Landscape	Hectares	Percent of Landscape
0 - 0.5 m	13267	15	1218	1.4
0.5 m - 1.0 m	315	0.4	112	0.1
>1.0 m	135	0.2	722	0.8
0 - 5 m	23244	26.3	1754	2
5 m - 10 m	41227	46.7	3015	3.4
10 m - 25 m	7069	8	63253	71.6
>25 m			7227	8.2
OPEN-HERB			4321	4.9
CLOSED-HERB	10	0	3639	4.1

Table 18: Percent of landscape for PIMOF cover classes for initiation and simulation data for 100 year simulation using A2 scenario.

	Snake Range Initiation Data		Snake Range 100-year Simulation Data	
Cover Class	Hectares	Percent of Landscape	Hectares	Percent of Landscape
>= 10 and < 20%	6168	7	20	0
>= 20 and < 40%	33746	38.2	4	0
>= 40 and < 70%	456	0.5	0	0
>= 70 and <= 100%	0	0	51924	58.8

Table 19: Percent of landscape for size classes of simulated data for 100 year simulation using A2 scenario, that began as shrub lifeform.

	Snake Range 100-year Simulation Data	
Size Classes	Hectares	Percent of landscape that began as shrub
0 - 0.5 m	1202	8.7
>1.0 m	428	3.1
5 m - 10 m	17	0.1
10 m - 25 m	11827	85.8
>25 m	17	0.1
OPEN-HERB	297	2.2

9 Appendix

Supplemental Tables

Table S1: Percent of landscape for each LANDFIRE vegetation type in the initialization data for the Clover Mtn. study area.

LANDFIRE Vegetation Name	Species Code	Hectares	Percent of Landscape
Great Basin Pinyon-Juniper Woodland	PIMOF	37839	84.5
Coleogyne ramosissima Shrubland Alliance	CORA	3650	8.1
Mojave Mid-Elevation Mixed Desert Scrub	CORA	1202	2.7
Inter-Mountain Basins Big Sagebrush Shrubland	ARTR2	706	1.6
Great Basin Xeric Mixed Sagebrush Shrubland	ARAR	624	1.4
Sonora-Mojave Semi-Desert Chaparral	QUTU	160	0.4
Inter-Mountain Basins Montane Riparian Systems	POFR	135	0.3
North American Warm Desert Riparian Systems	RIP	89	0.2
Mogollon Chaparral	QUTU	86	0.2
Developed-Open Space	NO CODE	66	0.1
Agriculture-Cultivated Crops and Irrigated Agriculture	NO CODE	40	0.1
Agriculture-Pasture and Hay	AGR	37	0.1
Barren	BA	30	0.1
Inter-Mountain Basins Mixed Salt Desert Scrub	ATCO-ARBI3	26	0.1
Quercus gambelii Shrubland Alliance	QUGA	23	0.1
Rocky Mountain Gambel Oak-Mixed Montane Shrubland	QUGA	19	0
Introduced Upland Vegetation-Annual Grassland	TALL-FORB	17	0
Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland	CELE	14	0
Open Water	WATER	7	0
Inter-Mountain Basins Semi-Desert Grassland	ACHY	4	0
Rocky Mountain Aspen Forest and Woodland	POTR5	4	0
Rocky Mountain Bigtooth Maple Ravine Woodland	RIP	4	0
Inter-Mountain Basins Semi-Desert Shrub-Steppe	ARTR2	3	0
Inter-Mountain Basins Sparsely Vegetated Systems	BA	3	0
Introduced Upland Vegetation-Annual and Biennial Forbland	TALL-FORB	3	0
Great Basin Semi-Desert Chaparral	QUTU	1	0

Table S2: Percent of landscape for each LANDFIRE vegetation type for initialization data for the Sheep Range study area.

LANDFIRE Vegetation Type	Species Code	Hectares	Percent of Landscape
Great Basin Pinyon-Juniper Woodland	PIMOF	14639	48.7
Mojave Mid-Elevation Mixed Desert Scrub	CORA	9068	30.2
Southern Rocky Mountain Ponderosa Pine Woodland	PIPO	3537	11.8
Great Basin Xeric Mixed Sagebrush Shrubland	ARAR	1223	4.1
Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland	ABCOC	897	3
Inter-Mountain Basins Montane Sagebrush Steppe	ARTR2	325	1.1
Inter-Mountain Basins Subalpine Limber-Bristlecone Pine Woodland	PIAR	202	0.7
Rocky Mountain Subalpine-Montane Mesic Meadow	TALL-FORB	48	0.2
Southern Rocky Mountain Ponderosa Pine Savanna	PIPO	36	0.1
Inter-Mountain Basins Montane Riparian Systems	POFR	33	0.1
Mogollon Chaparral	QUTU	29	0.1
Introduced Upland Vegetation-Annual and Biennial Forbland	TALL-FORB	24	0.1
Barren	BA	4	0
North American Warm Desert Riparian Systems	RIP	3	0
Sonora-Mojave Semi-Desert Chaparral	QUTU	1	0

Table S3: Percent of landscape for each LANDFIRE vegetation type for initialization data for the Snake Range study area.

LANDFIRE Vegetation Type	Species Code	Hectares	Percent of Landscape
Great Basin Pinyon-Juniper Woodland	PIMOF	39960	45.2
Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland	CELE	17369	19.7
Great Basin Xeric Mixed Sagebrush Shrubland	ARAR	8994	10.2
Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland	PIEN-ABLA	4692	5.3
Barren	BA	3447	3.9
Inter-Mountain Basins Big Sagebrush Shrubland	ARTR2	3063	3.5
Rocky Mountain Aspen Forest and Woodland	POTR5	2399	2.7
Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland	PSME-PIPO	2369	2.7
Abies concolor Forest Alliance	ABCOC	1686	1.9
Inter-Mountain Basins Subalpine Limber-Bristlecone Pine Woodland	PIAR	1380	1.6
Artemisia tridentata ssp. vaseyana Shrubland Alliance	ARTR2	857	1
Inter-Mountain Basins Mixed Salt Desert Scrub	ATCO-ARBI3	852	1
Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland	POTR5-PSME-PIEN-ABLA	514	0.6
Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland	ABCOC	432	0.5
Inter-Mountain Basins Montane Riparian Systems	POFR	89	0.1
Rocky Mountain Lower Montane-Foothill Shrubland	CELE	85	0.1
Snow-Ice	SNOW-ICE	43	0
Developed-Open Space	NF	32	0
Agriculture-Pasture and Hay	AGR	14	0
Inter-Mountain Basins Montane Sagebrush Steppe	ARTR2	13	0
Introduced Upland Vegetation-Perennial Grassland and Forbland	NF	12	0
Inter-Mountain Basins Big Sagebrush Steppe	ARTR2	9	0
Developed-Low Intensity	NF	6	0
Rocky Mountain Gambel Oak-Mixed Montane Shrubland	QUGA	4	0
Introduced Upland Vegetation-Annual and Biennial Forbland	TALL-FORB	3	0
Quercus gambelii Shrubland Alliance	QUGA	3	0
Introduced Upland Vegetation-Annual Grassland	TALL-FORB	1	0

Rocky Mountain Subalpine/Upper Montane Riparian Systems	RIP	1	0

Table S4: Percent of landscape for each LANDFIRE vegetation type in the Field Validation area.

LANDFIRE Vegetation Type	Species Code	Hectares	Percent of Landscape
Great Basin Pinyon-Juniper Woodland	PIMOF	210	77.9
Abies concolor Forest Alliance	ABCOC	26	9.5
Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland	PSME-PIPO	15	5.5
Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland	CELE	14	5.2
Great Basin Xeric Mixed Sagebrush Shrubland	ARAR	2	0.7
Rocky Mountain Aspen Forest and Woodland	POTR5	1	0.5
Artemisia tridentata ssp. vaseyana Shrubland Alliance	ARTR2	1	0.3
Inter-Mountain Basins Big Sagebrush Shrubland	ARTR2	0	0.2
Rocky Mountain Lower Montane-Foothill Shrubland	CELE	0	0.1
Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland	POTR5-PSME-PIEN-ABLA	0	0.0
Inter-Mountain Basins Big Sagebrush Steppe	ARTR2	0	0.0
Inter-Mountain Basins Subalpine Limber-Bristlecone Pine Woodland	PIAR	0	0.0
Southern Rocky Mountain Ponderosa Pine Woodland	PIPO	0	0.0

Table S5: Table of 2008 LANDFIRE modeled vegetation type for each of the randomly selected field validation pixels.

ID	Easting	Northing	Existing Vegetation Name
1	730064.7015	4309010.007	Great Basin Pinyon-Juniper Woodland
2	731114.7015	4308890.007	Great Basin Pinyon-Juniper Woodland
3	730124.7015	4308800.007	Great Basin Pinyon-Juniper Woodland
4	729734.7015	4308740.007	Great Basin Pinyon-Juniper Woodland
5	729434.7015	4308710.007	Great Basin Pinyon-Juniper Woodland
6	730334.7015	4308710.007	Great Basin Pinyon-Juniper Woodland
7	730184.7015	4308590.007	Great Basin Pinyon-Juniper Woodland
8	729284.7015	4308560.007	Great Basin Pinyon-Juniper Woodland
9	729524.7015	4308560.007	Great Basin Pinyon-Juniper Woodland
10	729854.7015	4308410.007	Great Basin Pinyon-Juniper Woodland
11	730664.7015	4308410.007	Great Basin Pinyon-Juniper Woodland
12	731234.7015	4308320.007	Abies concolor Forest Alliance
13	729374.7015	4308230.007	Great Basin Pinyon-Juniper Woodland
14	731054.7015	4308230.007	Abies concolor Forest Alliance
15	730364.7015	4308200.007	Great Basin Pinyon-Juniper Woodland
16	731174.7015	4308170.007	Abies concolor Forest Alliance
17	731234.7015	4308050.007	Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland
18	731264.7015	4308050.007	Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland
19	729164.7015	4307990.007	Great Basin Pinyon-Juniper Woodland
20	729674.7015	4307930.007	Great Basin Pinyon-Juniper Woodland