Project Title: Forecasting changes in sagebrush distribution and abundance under climate change: integration of spatial, temporal, and mechanistic models

Project type: Science Project 1A

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Project Objective(s): We will forecast the effect of climate change on the distribution and abundance of big sagebrush in order to inform conservation planning, and sage grouse management in particular, across the Intermountain West. The novelty of our work is the synthesis of models based on spatial, temporal, and mechanistic relationships between climate and sagebrush cover.

Management Objective(s): Sage grouse conservation is a top priority for the GBLCC, as well as other LCC's in the Intermountain West. The impending listing of the Greater sage-grouse has created science and conservation needs for the Great Basin, Great Northern, Southern Rockies, and Plains and Prairie Potholes LCC's. The Sage-Steppe Partner Forum (http://greatnorthernlcc.org/partner-forums/sage-steppe) includes all four LCCs and additional groups working "to develop a shared knowledge base around Greater sage-grouse, sagebrush habitat, and management across the species' historic range." One of the most difficult questions is how climate change will impact sage-grouse habitat, in particular the distribution and abundance of sagebrush (*Artemisia*). Current research on this topic is inadequate, relying solely on problematic species distribution models, and is poorly communicated to land managers. Our project will improve both the science and the communication of it to land managers.

Project Description:

1. Introduction

Big sagebrush (*Artemisia tridentata*) is a habitat-defining species in western North America, lending its name to two widespread vegetation types in Kuchler's (1964) map of the potential natural vegetation of the United States (Fig. 1). However, habitat conversion, biological invasions, and altered fire regimes have dramatically reduced the quantity and quality of sagebrush vegetation (Knick et al. 2003, Hanser et al. 2011), causing population declines in sagebrush-dependent wildlife species such as the Greater sage grouse (Aldridge et al. 2008). Climate change will further alter sagebrush abundance and distribution (Neilson et al. 2005), potentially exacerbating current habitat losses (Chambers and Pellant 2008). The future of sage grouse fundamentally depends on the future of sagebrush.

Despite the role of sagebrush as the foundation of many western ecosystems, we have limited ability to anticipate future impacts of climate change on sagebrush populations. In fact, this proposal represents an extension of an NSF-funded climate change vulnerability assessment for sagebrush steppe, led by PI Adler, which identified uncertainty about future changes in sagebrush populations as a critical constraint on climate change adaptation planning. Current efforts to forecast sagebrush habitat typically rely on species distribution models (SDMs). This approach provides valuable information about potential changes in climate suitability across broad spatial scales, but also suffers from a variety of well-known weaknesses, such as the assumption that current distributions are in equilibrium with climate, failure to account for dispersal limitation or species interactions, and statistical complications involving spatial autocorrelation and presence-only data sets (Guisan and Thuiller 2005). Our vulnerability assessment concluded that a forecasting approach based solely on SDMs would be inadequate. However, by integrating SDMs with complementary research approaches, such as historical data analysis and mechanistic models, we can provide increased confidence in projections of habitat change.

Our goal is to forecast the effect of climate change on the distribution and abundance of big sagebrush in order to inform conservation planning, and sage grouse management in particular, across the Intermountain West. The novelty of our work will be the synthesis of models based on spatial, temporal, and mechanistic relationships between climate and sagebrush cover.

2. Proposed activities

Our proposed research will focus on two objectives:

1. Project future changes in sagebrush cover based on i) regional, spatial relationships between climate means and sagebrush cover, ii) local, temporal relationships between inter-annual variation in climate and sagebrush cover, and iii) mechanistic relationships between environmental drivers and sagebrush performance.
2. Synthesize projections from the independent approaches (Objective 1) to forecast the direction, magnitude, and uncertainty of changes in sagebrush cover across the Intermountain West and disseminate this information to land managers.

2.1. Projections of sagebrush cover based on diverse modeling approaches

Spatial relationships between climate and sagebrush cover

Current models of climatic suitability for *A. tridentata* are based on presence-only data (Bradley 2010; Schlaepfer et al. 2012c). These traditional SDMs can project changes in distribution (occupancy), but correlate poorly (VanDerWal et al. 2009; Tôrres et al. 2012; Estes et al. 2013) or not at all (Pearce and Ferrier 2001; Nielsen et al. 2005; Jimenez-Valverde et al. 2009) with species abundance. For a regionally distributed, dominant species such as *A. tridentata*, dramatic changes in abundance across the core of its range may have larger ecological consequences than changes in distribution at range margins. Fortunately, where regional cover data are available, suitability models can effectively predict continuous cover (e.g., Kulhanek et al., 2011; Estes et al., 2013). Sagebrush ecosystems present a unique opportunity to spatially model continuous cover because of the availability of regional cover data.

We will model continuous sagebrush cover data using field data from the southwest and northwest ReGAP analysis program, which collected thousands of plot-level vegetation cover estimates across the west in the mid-2000s, along with plot level cover estimates from VegBank (vegbank.org) and Aldridge's remote sensing work in Wyoming (Homer et al. 2012). We have already acquired all these datasets. We will randomly subset the data to select 70% of the plots for training and will reserve 30% for evaluation.

We will test several standard approaches to model continuous cover as a function of climate (e.g., GLM, GAM, random forest/CART). We will use an information theoretic approach to select the best climate predictors from the following set of 30-year (1980-2010) averages derived from from PRISM (Daly et al., 2002): mean, maximum, and minimum seasonal temperatures, mean daily temperature variation for each season, mean seasonal precipitation total, and interannual variation in precipitation for each season. We will project changes in cover using based on downscaled climate projections using the CMIP5 multi-model ensemble (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/9). We will repeat the projection for the most and least conservative greenhouse gas emission scenarios (RCP 2.5 and RCP 8) included in this ensemble.

Temporal relationships between climate and sagebrush cover

Our SDM projections rely on spatial relationships between climate and cover to make predictions about long-term changes in cover at specific locations. An independent and complementary approach focuses instead on patterns of interannual variation in climate and cover (Munson et al. 2012, 2013). Cover of sagebrush on permanent monitoring plots varies over time in response to survival, growth and recruitment, and climate is a primary driver of such fluctuations. By understanding how historical variation in climate drives increases and decreases in cover, we can predict how future shifts in climate will impact sagebrush cover.

To date, we have collected multi-year datasets of sagebrush cover or biomass from 17 monitoring or research projects, spanning a large portion of the sagebrush distribution from Arizona to Montana. We have also compiled precipitation and temperature data from PRISM for all of these sites. Each year-to-year change in sagebrush cover gives us a data point showing how sagebrush cover responded to the weather at that site in that year. Regression models relating the observed change in cover to annual weather (e.g. spring temperature or winter precipitation). We will use the regressions to select climate covariates from the same set of seasonal climate descriptors used for the spatial models (above) with one important difference: While the spatial models use 30 yr means for each climate descriptor (e.g. mean spring temperature for a 30 yr period), our temperature models will use the observed temperature from a specific year (e.g. mean spring temperature in 2006). Our preliminary analysis shows that sagebrush cover tends to increase with precipitation and decrease with spring temperature (Fig. 2). The complete data set will allow us to characterize how such responses vary across the region.

Mechanistic models

The spatial and temporal approaches we have described are purely empirical: they consist of correlations between climate variables and cover. We will complement these approaches with two mechanistic models that incorporate biophysical and ecophysiological processes.

Our first mechanistic model focuses on sagebrush germination and establishment. In locations where sagebrush cannot regenerate following fire (Nelson et al. 2014) or climate-driven die-offs (Hanson et al. 1982, Cárdenas et al. 1997), it will not persist in the future. Furthermore, regenerative stages may be particularly sensitive to climate (Grubb 1977); big sagebrush does not re-sprout and relies entirely on seeds for regeneration, which requires an infrequent combination of suitable conditions (Schlaepfer et al. in review). The strong dependence of sagebrush on seasonal timing of moisture will allow us to apply a new mechanistic model of potential germination and first-year seedling survival (Schlaepfer et al. accepted) to project the impact of climate change. The model was trained for big sagebrush with a total of 1435 site-years of observations and explained 74% of the variation in regeneration success (Schlaepfer et al. accepted). The model is unique in its treatment of snow cover and soil water dynamics throughout the rooting zone (Schlaepfer et al. 2012b, a, Schlaepfer et al. in review). The regeneration model requires daily forcing data of air and top-soil temperature, soil water potential in soil layers, and snow cover. We will use SOILWAT, a daily-time step ecosystem soil water balance simulation model (Parton 1978, Sala et al. 1992, Schlaepfer et al. 2012b, c, a), to generate the forcing data for the regeneration model. We will run the regeneration model for the same grid cells covered by the SDM, using cell-specific daily weather data from the CMIP5 ensemble, along with soil information, and estimations of vegetation composition, biomass and seasonal phenology.

A dynamic global vegetation model (DGVM) represents our second mechanistic approach. DGVMs combine principles from biogeography and biogeochemistry to model establishment, growth, and mortality at the plant functional type level. The DGVM concept is typically applied at continental to global scales, but the mechanistic framework also can be applied to regional-scale problems. Presently, most DGVM models ignore shrub vegetation, or if shrubs are included, they are represented as ‘small trees’ via modifications in allometry. With the proposed support for a post-doctoral fellow, we will build bioclimatic and physiological parameter files for an *Artemisia* sagebrush functional type to be simulated by the LPJ-GUESS DGVM, a biogeochemical forest ‘gap’ model. The post-doc will develop these files by searching the literature for data on traits related to bioclimatic constraints on establishment, resource utilization for light, water, nutrients, and carbon allocation and allometry, and responses to fire disturbance.

A new mechanistic fire module embedded in LPJ-GUESS, currently in development at Montana State University, will allow us to study the interaction between climate change and fire. The fire module simulates human and natural ignitions, the rate of spread and intensity of fire, and fire effects on vegetation. The distribution and cover of big sagebrush is extremely sensitive to fire and increasing fire frequency across the west is a prominent threat to sagebrush ecosystems. Based on a recent analysis, nearly 9000 km^2 of sagebrush burned during the 2000s (Balch et al., 2013). However, we have little understanding of how climate change will alter fire frequency in sagebrush ecosystems, or how that influence may vary across the species’ range. Ongoing research by Bradley and Balch is investigating how fire probability relates to interactions between climate conditions and invasive annual grass fuel loads. Bradley’s lab has already compiled and processed MODIS burned area data from 2000-2012. The post-doc will extend this work to document relationships between climate, fire, and sagebrush fuel loads. We will use subsets of this observational record to parameterize a regional fire danger index, fire spread, and fire intensity algorithms implemented in LPJ-GUESS, whereas decadal trends in observed fire activity will be used as a benchmark for evaluating model performance.

2.2. Synthesis and outreach to land managers

Our four models focus on slightly different responses: While the SDM and DGVM both will produce spatially explicit maps of sagebrush cover, our temporal model focuses on population growth rate and the regeneration model predicts the probability of establishment. Therefore, in order to assess the consistency of these models, we will conduct a sensitivity analysis. We will quantify the change in each model’s respective measure of sagebrush performance given a small perturbation in one climate covariate, such as spring temperature or winter precipitation. For the empirical models, this sensitivity is equivalent to the slope of the statistical relationship of interest at a particular location (e.g. pixel or monitoring site). For the mechanistic models, the sensitivity must be evaluated using a dynamic simulation in which the climate covariate of interested is perturbed. The key is that, for all four models, we can directly correlate the projected changes in sagebrush performance caused by the change in the climate covariate (Fig. 3). Because climate covariates are selected independently for each of the four models, a particular climate driver of interest may not be included in every model. Thus, differences in model selection are one possible source of differences in model projections.

We will gain confidence in our ability to identify areas vulnerable to climate change if the sensitivity analysis shows consistency among all four models about areas where warming will cause reductions in sagebrush cover, population growth rates or establishment probability. Conversely, in portions of the region where different research approaches generate conflicting results, we would have very low confidence in the predicted change. To communicate our results to land managers, we will create a schematic synthesizing our confidence in trends in cover at different elevations and portions of the region (Fig. 4), deliberately avoiding fine resolution output which typically implies greater certainty than we have. To maximize relevance for sage-grouse managers, we will focus on projected changes in sagebrush cover in the sage-grouse Priority Areas for Conservation (PACs; US Fish and Wildlife Service 2013).

Project Products:

Peer reviewed publications - We anticipate publishing peer-reviewed papers on each of the SDM, DGVM, and long-term data analyses, as well as a synthesis paper evaluating the strength of evidence for projected changes in sagebrush cover across the region. Expected outlets include *Ecological Applications*, *Global Change Biology*, and *Biological Conservation*.

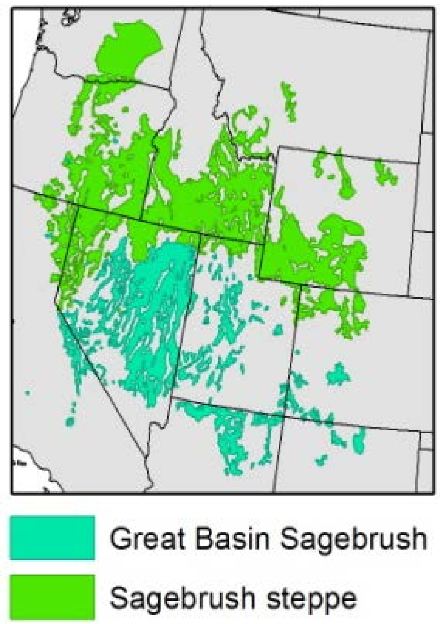
Information for land managers - We will include our schematic forecasts (Fig. 4) in a synthesis report written for land managers that we have already begun as part of Adler's NSF-funded vulnerability analysis. That project, which is focused on strengthening relationships between researchers and land managers, has directly engaged state extension and federal land management agencies. Thus, we already have mechanisms in place to efficiently disseminate important new research.

Data sets and models - Given the interest in sage grouse conservation planning, we expect demand for our data and results. As described in the Data Management Plan, we will freely distribute all of our model projections and all raw data and computer code not constrained by intellectual property rights.

Communication & Engagement: An essential feature of this project, and the vulnerability assessment it grew out of, is the involvement in all stages of the work of land managers from the BLM, US Forest Service, National Parks Service, and The Nature Conservancy. The managers will critique our research objectives before we begin analyses, review the results as they develop, and then partner with researchers to write a synthesis report for a land manager audience. Drafting of this synthesis report is the primary purpose of the working group meeting we have proposed. The centerpiece of the report will be a schematic figure visually representing our confidence in sagebrush cover projections for sage-grouse PACs. We will distribute the report through a network of partners we have already built and which includes university extension, the Great Basin Research and Management Partnership, and the USGS. We will work with Todd Hopkins (Great Basin LCC) to communicate our findings via the Sage-Steppe Partner Forum and presentations at the annual Great Basin Consortium meeting.

Figures and Tables

Fig. 1. Distribution of sagebrush-dominated potential vegetation in the US.



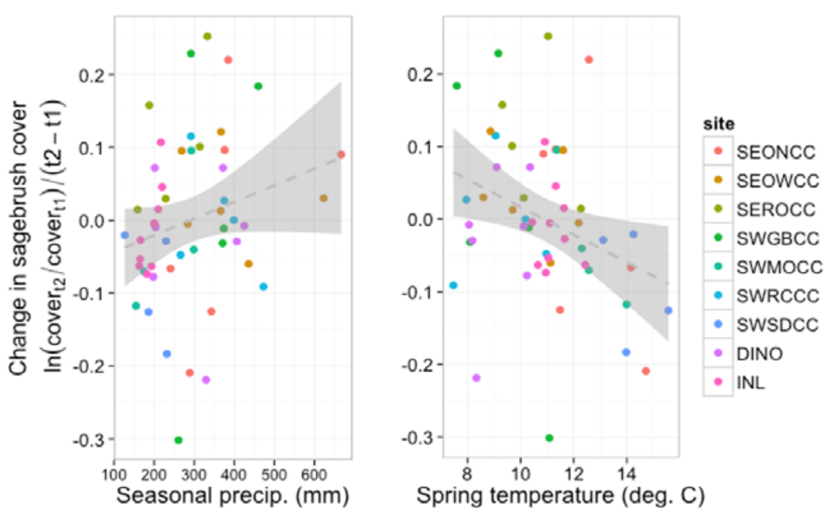


Fig. 2. Preliminary data showing change in sagebrush cover over seasonal precipitation (left) and spring temperature (right). A value of zero indicates no change in cover. Colors correspond to the location of multi-year plot monitoring data: Idaho Natl. Lab. (INL), Dinosaur Natl. Monument (DINO) and SageSTEP control plots (SEONCC – SWSDCC). Gray dashed line shows linear regression fit to data plus and minus standard error.

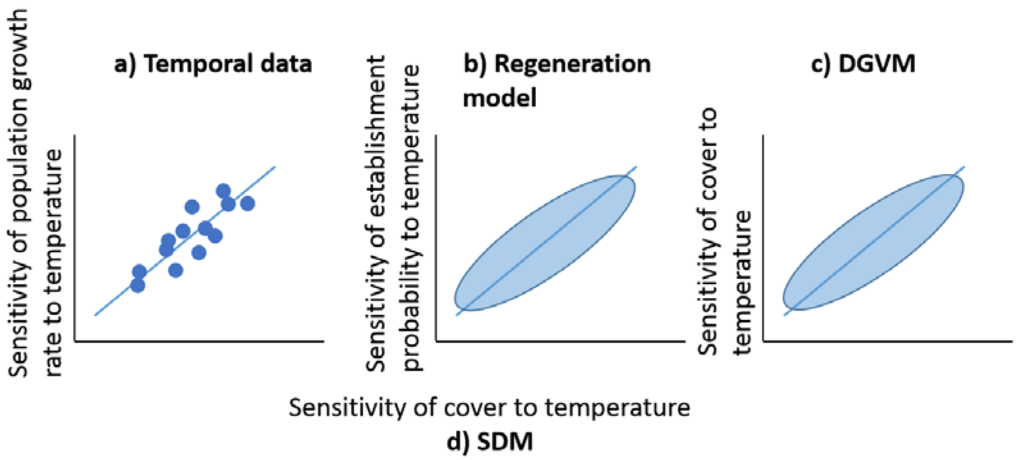
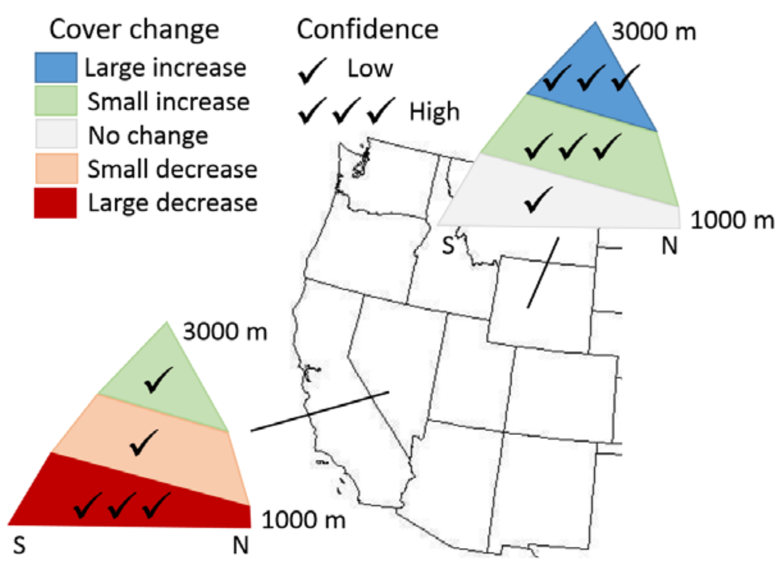


Fig. 3. Hypothetical results comparing temperature sensitivity of the SDM (x-axis) with temperature sensitivity of the a) temporal and b,c) mechanistic models (y-axes). In a), the dots show predictions for local study sites distributed across the sagebrush region (see Fig. 2). The DGVM and regeneration models will generate gridded predictions at the same resolution as the SDM; the ellipses indicate a cloud of data corresponding to grid cells covering the region.

Fig. 4. Hypothetical example of a synthesis product for land managers. The goal is to communicate our confidence in future changes in sagebrush cover at different elevations and portions of the region for a specific IPCC emissions scenario.



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