NC CSC Foundational Science: Impacts and Vulnerability

Andrew Hansen
Montana State University
Bozeman, MT 59717
Hansen@montana.edu

Summary

The goal of the proposed work is to assess the vulnerability of forest and grassland vegetation to climate change and drought in the greater ecosystems centered on public and Native American lands across the North Central Climate Science Center (NC CSC) domain. Objectives are as follows.

1. Quantify change in the spatial patterns of natural cover types as influenced by land use intensification for 2000 to present and projected to 2100.
2. Summarize the responses of ecological processes to past (1950-present) and projected (2010-2100) climate change.
3. Develop species habitat distribution models for dominant forest / shrub species and project species habitat suitability under IPCC climate scenarios.
4. Statistically relate grassland phenology to climate, soils, and landform and project potential changes in grassland phenology under IPCC climate scenarios.
5. Synthesize the results from Objectives 1-3 in the form of vulnerability assessments for major greater wildland ecosystems in the NC CSC domain.

The study area includes the forest, shrubland, and grassland cover types across the NC CSC domain. The spatial units for analysis include the Greater Wildland Ecosystems centered on federal and Native American lands and EPA Type III ecoregions. Objective one will analyze the rates and patterns of fragmentation of natural cover types by human land use in the recent past and projected into the coming century. Objective 2 will summarize the responses ecological processes to past (1950-present) and projected (2010-2100) climate change. PRISM data, IPCC CMIP 5 climate projections and land use change projections will be inputs to the TOPS ecological model to project snow pack, soil moisture, runoff, and gross primary productivity. Objective 3 will develop species habitat distribution models for dominant forest / shrub species and project species habitat suitability under IPCC climate scenarios. Forest Inventory and Analysis data will be used to develop statistical models using the SAHM software and project tree species habitat suitability under future climate scenarios. Objective 4 will employ MODIS NDVI data to develop statistical models of grassland phenology based on climate, soils, and landform and project potential changes in grassland phenology under IPCC climate scenarios. Objective 5 will synthesize the results from Objectives 1-4 in the form of vulnerability assessments for major Greater Wildland Ecosystems in the NC CSC domain.

Public Summary

Rates of climate change vary across the Great Plains and Rocky Mountains as do the responses of ecosystems to these changes. Knowledge of locations of rapid climate change and changes in ecosystem services such as water runoff and ecological productivity are important for crafting locally relevant adaptation strategies to cope with these changes. This project will assess how climate, ecosystem processes, and vegetation have shifted over the past half century and how they are projected to change in the coming century under various future scenarios. These analyses will be done within areas centered on natural vegetation cover such as in and around Federal and Native American lands. These areas of natural vegetation provide ecosystem services important to local people and knowledge of patterns of climate and ecological change are important to resource managers. The results of the project will be used by the NC CSC Adaptation team to work with local stakeholders to develop strategies for coping with and adapting to the projected changes.

Project Description

Introduction

The NC CSC efforts have been framed as a Resource for Vulnerability, Adaptation, and Mitigation Planning (ReVAMP). **The vision for the NC CSC is a coordinated and integrated regional science approach for the management of the nation's land, water, fish and wildlife, and cultural resources -- resources that utilize the best possible understanding of past, present, and future climate to inform decision processes.**

The NC CSC is working to provide the understanding and information needed by US Department of Interior decision makers and managers in the region so that a more complete understanding of potential impacts and adaptation strategies for a broad range of natural, cultural, energy, and other resource management activities will be available. The objective of ReVAMP is to develop a regional resource for agency scientists and managers to access and utilize the best available climate science and synthesis to inform their strategic planning and management decisions. The NC CSC staff with the foundational science team will take the lead on defining and operationalizing the ReVAMP. This development will include close collaboration with the funded NC CSC projects and this collaboration will be facilitated through a set of activities and access to research tools and analyses.

The ReVAMP concept serves as the centralizing theme to coordinate research done through the NC CSC and will also provide the mechanism by which the NC CSC can help serve stakeholder needs (NC CSC Science Strategy, 2013). The NCUC efforts are organized around three foundation research themes, which are meant to form an integrated approach to inform resource managers and researcher in our region:

- Understanding and quantifying drivers of regional climate changes,
- Assessing impacts of climate change on the natural resources of the region and the resulting vulnerability of social-ecological system components, initial activity will be focused on ecosystem elements with development of strategy to expand to the integrated system; and
- Characterizing Social-ecological Systems (SES) vulnerabilities, adaptive capacities, and management response options of communities and natural resource managers

Across the north central domain, a dominant climate feature affecting natural resources is drought, and the funded projects of the NC CSC have aspects of drought impacts to consider within their projects. The joint research activities will work toward the development of an analytical framework and information to determine the various underlying climate factors leading to drought conditions and how these may be different in the future, evaluating the impacts and consequences of different drought situations affecting different management decisions across our domain, and to assess adaptive capacities and response strategies in the management communities. This proposal builds on that foundation and describes some explicit activities that help extend the foundational science areas and establish the ReVAMP concept.

Drought has expressed itself across the region in response to periods of low precipitation, to periods of extended elevated temperatures, or to a combination of these climate conditions. Future scenarios across the region suggest that temperature increases will exacerbate environmental conditions, which would lead to greater drought effects, through increased evapotranspiration, for example, despite the level of changes in precipitation taking place. The notable exception is the Red River of the North area in North Dakota where saturated soils and increased spring rainfall have been leading to floods in recent years.

Across the domain drought can be driven from a variety of predominant climate factors. The various drought climate impacts, ecosystem responses, and social-ecological system management issues will serve as useful case studies for the foundational science areas to develop integrative analytical tools to address their considerations. For instance, Greater Yellowstone area in the U.S. Northern Rockies faces periods of extended drought due to changing snowmelt timing and increased warming resulting in reduced soil moisture conditions. This reduction in soil moisture during the whitebark pine growing season has contributed to an increased vulnerability to pine bark beetle and other pathogens affecting this population of trees. In the other projects, drought conditions have some similar, but some differently expressed drought characteristics, impacts and management capacities and responses. The response strategies in these areas will also be developed differently due not only to the natural resource impact, but due to the social and institutional contexts and capacities of the respective management entities.

Given the pervasive nature of drought across most of the region and the complex interactions associated with climate conditions leading to drought, the differential sensitivity which different species and ecosystems express to these conditions, and the varied capacity to respond and to manage for drought, we plan a set of coordinated research and analysis to better understand the nature and impacts of drought across the region.

The overall Foundational Science objectives are:

1) Evaluation and synthesis of climate conditions in different regions of the North Central domain which would lead to drought condition (e.g., extended heat conditions, extended periods of low precipitation, or a combination of both) and the large-scale climate drivers of these local conditions, evaluation of climate products that are related to drought (for example, evapotranspiration datasets), and synthesis of existing information on drivers of drought in the North Central domain.

2) Assess the sensitivity to the range of drought conditions (i.e., climate-related drought exposure) affecting biodiversity and ecosystems across the region.
3) Assess the range of adaptive capacities and response strategies of different managers.

The role of the Foundational Science Teams in the NC-CSC differs from that of Funded Projects. The Teams will engage in the development the ReVamp framework to support the present and future activities of the NC CSC through the collaborative development and integration of datasets, tools, and guidance. The Teams will provide synthesis of science, impacts and vulnerabilities, and adaptation management challenges and strategies across the NC CSC region, and develop and document the use of these tools through interactions with the Funded Projects. We propose to focus many our team efforts on the theme of Drought: Drivers, Impacts, and Adaptation for the duration of this plan.

Goal and Objectives

The goal of this project is to assess vulnerability of forest and grassland vegetation to climate change and drought in the greater ecosystems centered on public and Native American Lands across the NC CSC domain. Specific objectives are as follows.

1. Quantify change in the spatial patterns of natural cover types as influenced by land use intensification for 2000 to present and projected to 2100.
2. Summarize the responses ecological processes to past (1950-present) and projected (2010-2100) climate change.
3. Develop species habitat distribution models for dominant forest / shrub species and project species habitat suitability under IPCC climate scenarios.
4. Statistically relate grassland phenology to climate, soils, and landform and project potential changes in grassland phenology under IPCC climate scenarios.
5. Synthesize the results from Objectives 1-4 in the form of vulnerability assessments for major Greater Wildland Ecosystems in the NC CSC domain.

Background on the Proposed Work

Federal land managers are increasingly concerned about how climate change may be affecting natural resources and ecosystem services. The rates and ecological impacts of climate change over past decades are known to vary geographically across the United States (Karl et al. 2009). Climate warming and drying has been particularly pronounced within western states, resulting in earlier start of growing seasons, increased frequency of severe fires, widespread forest pest outbreaks, and drought-induced forest mortality (Westerling et al. 2006, Allen et al. 2010). These factors in combination have led to large scale forest die-off especially in the southwestern deserts, the Rocky Mountains, and the Sierra Nevada (Breshears et al. 2005) and include keystone tree species such as Whitebark pine (*Pinus albicaulis*) (Logan et al. 2010) and Joshua tree (*Yucca brevifolia*) (Cole et al. 2011). In the coming decades, climate is expected to warm substantially across the western U.S., and is projected to change the phenology, productivity, and composition of vegetation (McKinney et al. 2011, Coops and Waring 2011, Gray and Hamann 2013, Polley et al. 2013, Bell et al. 2014). Understanding vegetation response to climate change is vital to designing strategies to cope with pending changes (Joyce et al. 2013).

Natural forest, shrubland, and grassland vegetation is of high interest under climate change because of its influence on ecosystem services and biodiversity. Future changes in vegetation life form, for example from forest to shrub, will likely affect mountain ecosystem function across the mountain west. Subalpine conifer forests in particular, control snow accumulation and melt, which in turn largely determines summer stream and river base flows that support downstream aquatic species and human use (Pederson et al. 2006). There is already ample evidence that warming springtime temperatures alone are leading to earlier spring snow melt, peak runoff, and lower summer baseflows and this trend is expected to continue (Pederson et al. 2011). Should subalpine forests be replaced by shrublands in a future hot and dry climate, it is likely that water resources throughout the snow-dominated mountain west would be further threatened. In general, forest loss in favor of vegetation communities of lower biomass like shrublands would also result in a net release of carbon and decrease in the ability of these ecosystems to fix carbon in the future (Allen et al. 2010). Examining the vulnerability to climate change of the dominant vegetation species in multiple communities and across plant life forms is a critical first-step in understanding the likely consequences of future ecological change.

Many wildlife species (i.e. biodiversity) in the Great Plains and Rocky Mountains are dependent on resources provided by the dominant vegetation of their habitat and could be adversely affected by vegetation change in the future. Greater sage-grouse for example, is already severely at risk due to degradation of sagebrush communities throughout much of its current range (Schroeder et al. 2004). This is at least in part due to human activity and patterns of land ownership that primarily protects higher elevation forests for biodiversity conservation while lower elevation shrub and grasslands are often developed for human use (Piekielek and Hansen 2012). Lower treeline forests of limber pine and juniper (many species) are also largely on private lands and provide important bird nesting habitat and browse for ungulates. Moderate elevation montane forests often straddle the public/private interface and provide the primary habitat for the American marten among other wildlife species of high conservation interest. The highest elevation forests in the subalpine environment are almost entirely on public lands and support the Clark's nutcracker and grizzly bear, among other species (Despain 1990). Native grasslands across the Great Plains have been heavily fragmented by agriculture and other intense land uses (Drummond et al. 2012). Consequently, wildlife species associated with prairie are among the most endangered in the US.

A key step in the climate adaptation framework adapted by the NC CSC (described above) is vulnerability assessment. Ecological vulnerability to global change refers to the extent to which a species, ecosystem, or ecological process is susceptible to harm from the direct and indirect impacts of climate and land use change (Schneider et al. 2007). These assessments aim to determine which conservation targets are most vulnerable, where they are vulnerable, and why they are vulnerable (Stein et al. 2014). Understanding how species, ecosystems, and ecological processes are already affected by global change and how they are likely to fare under future conditions is essential for developing enduring adaptation strategies. Vulnerability is evaluated in terms of three components. Exposure is the degree of change in climate and land use, which are key drivers of ecological processes and biodiversity. Sensitivity is the degree to which species and ecological processes respond to a given level of exposure, largely based on the environmental tolerances of organisms. Exposure and sensitivity determine the potential impact on the resource of interest. Adaptive capacity is the ability of a system to adjust to the elements of exposure. It is the interaction of potential impact and adaptive capacity that determines vulnerability.

During the first two years of NC CSC foundational science research, we made considerable progress on assessing vulnerability of vegetation composition across the Rocky Mountain portion of the CSC. This was done for the historic period of 1900 to present to provide context and projected to 2100 to explore potential consequences of alternative future scenarios. Exposure was represented as change in change in climate and land use (e.g., Chang and Hansen 2013, Gross 2013). Historic climate data came from PRISM (http://prism.oregonstate.edu) and future climate from IPCC CMIP-5 projections downscaled by Thrasher et al. (2013). Sensitivity of ecosystem processes and vegetation to climate change was quantified through models relating ecosystem performance and species tolerances to current climate conditions. Potential impact was assessed by using the models to project ecosystem and species responses under protected future climate conditions. The NASA-supported Terrestrial Observation and Prediction System (Nemani et al. 2009) was used to simulate snowpack, runoff, soil moisture, and primary productivity. Statistical models were used to project tree and shrub species habitat suitability under changing climate (Bell et al. 2012, 2013, Monihan et al. 2013, Chang et al. 2014, Piekielek et al in review). In these applications, expert opinion from scientists and managers was used to gauge the adaptive capacity of ecosystems and species to these potential impacts. The results were used to assess the vulnerability of tree and shrub species to climate change across the US Northern Rockies and within the Greater Ecosystems surrounding the major national parks (Hansen and Phillips in press). These vulnerability assessments are now being used by federal agency collaborators to prioritize adaptation strategies for vulnerable elements (e.g., NC CSC funded Whitebark pine restoration project). For an application of this vulnerability assessment approach to US national parks, see Hansen et al. (2014). We propose to expand this work to the NC CSC domain and add consideration of grassland phenology to the vulnerability assessment as a basis for adaptation planning across the NC CSC.

Proposed Research

Study Area. The project will focus on the public and private lands across the NC CSC domain that support natural vegetation cover types. Results will be summarized across the study area, within EPA Type III ecoregions, and within "Greater Wildland Ecosystems" (GWEs) (Figure 1). Ecoregions continue to be used as units for assessment by the US National Assessment (Melillo et al. 2014) and other organizations and we will summarize results within them. GWEs are the ecosystems centered on large tracts of public lands, They include federal and Native American lands which are dominated by wildland or natural resource extraction land uses, and surrounding private lands, which grade in land use from wildland to urban. In the context of global change, such areas of mixed ownership and land allocation are increasingly the spatial domains of coordinated adaptation planning and management (Hansen et al. 2014).

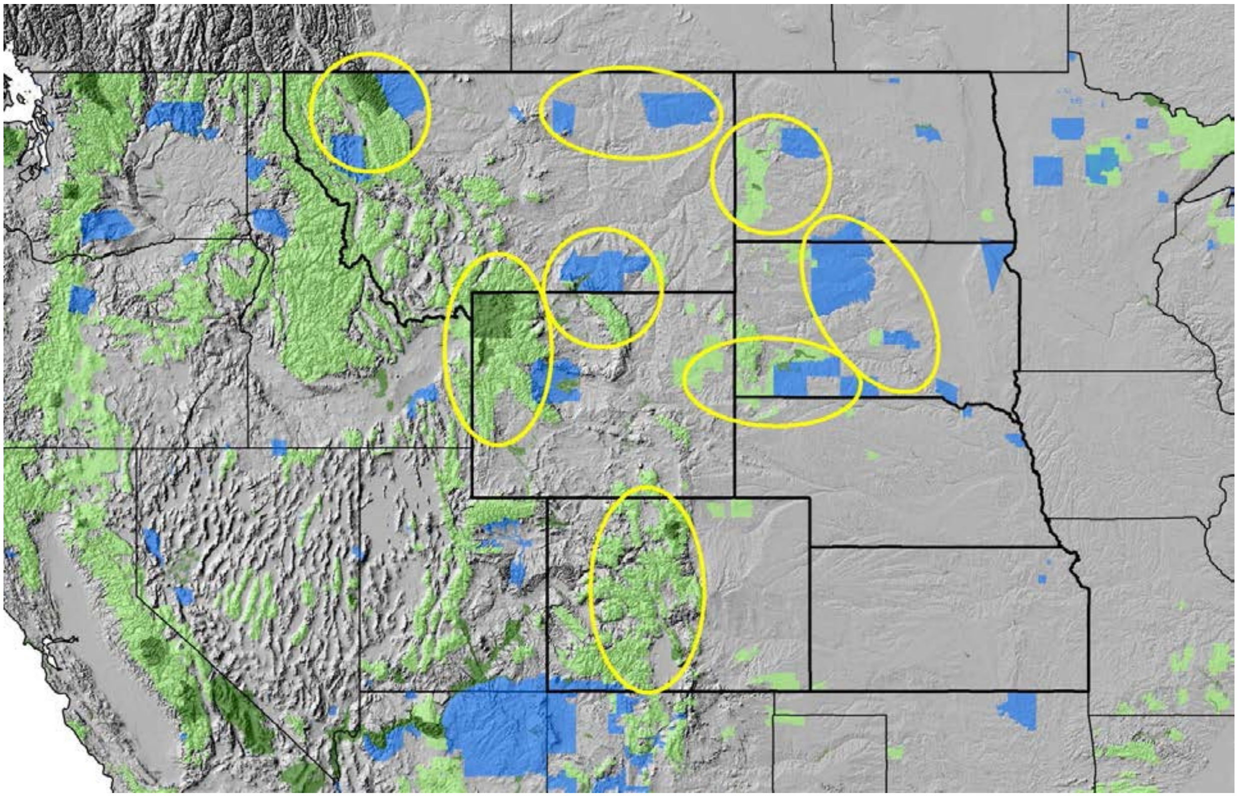

Figure 1. Map of the study area showing national forests (light green), national parks (dark green), Native American Lands (blue), and Greater Wildland Ecosystems (yellow polygons).

Obj 1. Fragmentation of natural cover types by land use. Natural vegetation cover types are of high interest in the NC CSC for the ecosystem services they provide and the biodiversity they support. The opportunity for adaptation planning under global change is influenced by the aerial extent and spatial configuration of these natural cover types. The U.S. Geological Survey (USGS) has quantified land cover and use and change in these during 2001-2011. USGS has also projected change in land cover and use to 2100 under downscaled IPCC social and economic scenarios. We will use these land cover and use data sets to quantify change in the distribution of natural cover types for 2001-2100.

Land cover and use data for the historic period of 2001-2011 will be derived from the USGS National Land Cover Database (NLCD) (http://www.mrlc.gov/). They mapped at a 30-m resolution land cover and use for the years 2001, 2006, and 2011 within 20 classes that include natural vegetation cover, and developed and agriculture land uses. Building on the NLCD and the USGS Land Cover Trends Project (Loveland et al. 2002), USGS downscaled IPCC SRES scenarios to ecoregional level and spatially allocated 11 classes of land cover and use at a 90-m scale across the US at 10 year intervals for 2010-2100 (Sleeter et al. 2013). These classes include natural forest and grassland cover types and agriculture and developed classes.

We will analyzed change in the spatial dimensions of natural cover types under this land use change. The base 30-m cells that meet the criteria of natural cover types and are > 0.5 km from other land use types will be grouped into patches following our previous methods of Wade and

Theobald (2010). The metrics of interest relate to area, shape complexity and connectivity. Fractal dimension is a measure of patch shape complexity and has been shown to be a significant correlate of extinction risk in vulnerability assessments (Pearson et al. 2014). Connectivity will be calculated by two metrics, Ti and Probability of connectivity index (Wade and Theobald 2010). The Ti metric accounts for both patch characteristics and effective distance of the entire network, but is measured for each patch. It builds on metapopulation dynamics approaches that differentiate pathways that have the same length, but contain a different number of intermediate patches to account for 'stepping-stones". Probability of connectivity index measures the probability that an organism located randomly on a patch in a network can reach another patch in the network. A decreasing exponential function relating least-cost distance to dispersal probability will be fit for three dispersal distances (10, 100, 1000 km). These metrics will be output for 2014-2100. The results will be summarized in spatial units that are relevant to conservation and management: ecoregions and GWEs.

Obj. 2. Summarize ecological processes response to climate change. In a related project, we used the Terrestrial Observation and Prediction System (TOPS) to hindcast (1950-2010) and forecast (2010-2100) ecosystem processes under IPCC CMIP-5 climate scenarios for the U.S. Northern Rockies (Melton et al. in prep) (Figure 2). Sponsored by NASA, the TOPS framework integrates operational satellite data, microclimate mapping, and ecosystem simulation models to characterize ecosystem status and trends. Key outputs are snowpack, runoff, soil moisture, and gross primary productivity. These TOPs runs were done for the contiguous U.S. The runs were done for two time periods: a baseline period spanning 2001-2010, and a forecast period

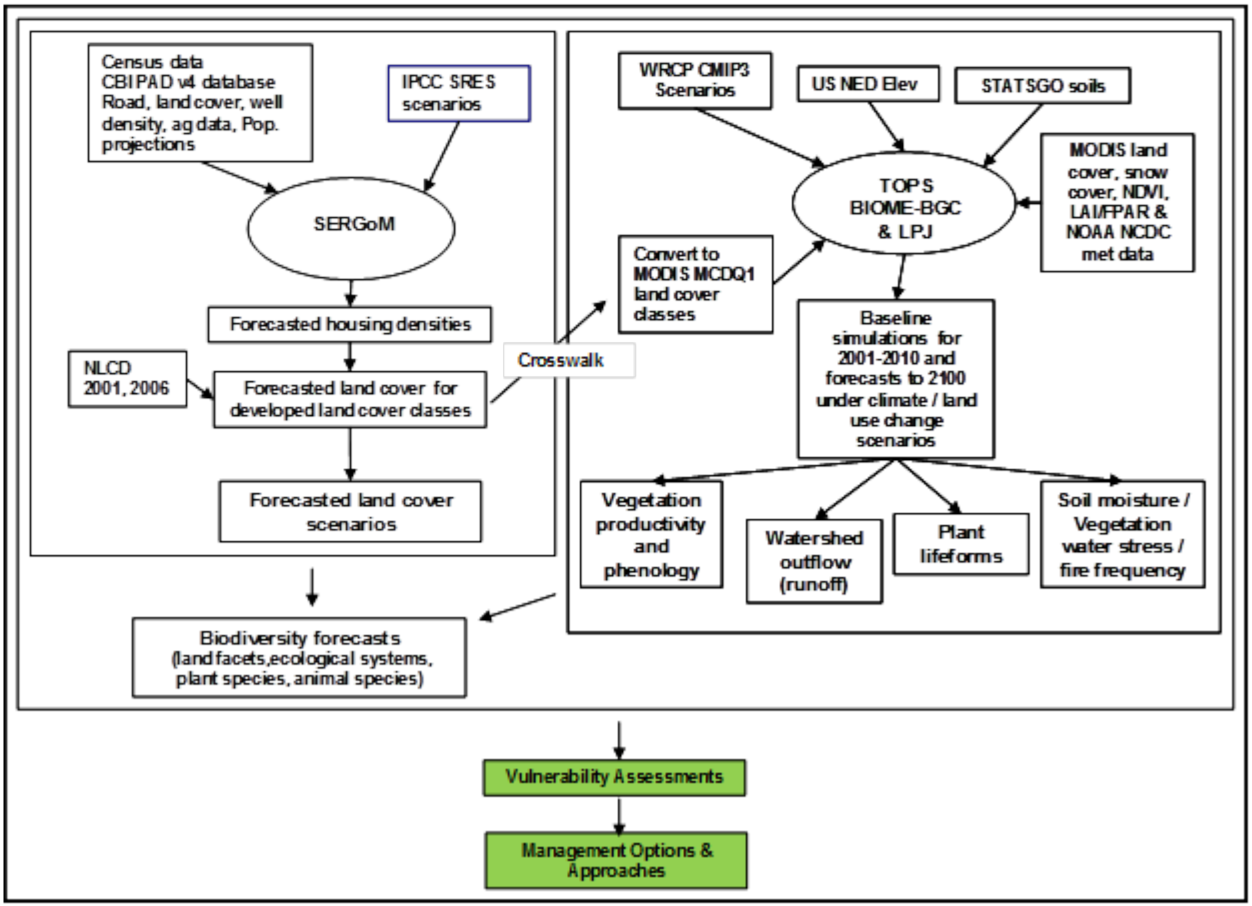

Figure 2. Overview of the components and data flow for the ecosystem processing modeling effort used by Melton et al. (In Prep.). The products from that study will be analyzed for the NC CSC domain.

spanning 2010-2100. Runs for the baseline period, were driven by TOPS in both prognostic and diagnostic modes. In diagnostic mode, TOPS utilized interpolated meteorological surfaces from the Surface Observation Gridding System and MODIS data including observations of snow cover, leaf area index, NDVI, land cover, and land surface temperature to drive the component models. In prognostic mode, the various photosynthetic and nutrient cycling processes were simulated by the model without integration of satellite inputs, and the downscaled climate change scenarios were used to drive the model. A comparison of estimates of gross primary productivity and streamflow from the prognostic and diagnostic simulations for the baseline period was made against observations from the USGS streamflow gauges and U.S. Fluxnet sites to characterize (1) uncertainty inherent in the model simulations in diagnostic mode, and (2) the additional uncertainty introduced when the models are run in prognostic mode and driven by the climate scenarios. Land cover data were updated on a decadal timestep based on the SERGoM land use model. Outputs from SERGoM were crosswalked to the MODIS MOD12Q1 Type 3 land cover (LAI/fPAR biome type) and LPJ lifeforms to facilitate these updating. Outputs from the TOPS project are stored on the NASA Earth Exchange (NEX), from which we will extract those for natural cover types within the NC CSC area and summarize the hindcasts and forecasts for ecoregions and GWEs.

Obj.3. Project habitat suitability for tree and shrub species. We will expand our modeling of vegetation habitat suitability in the U.S. Northern Rockies to all the naturally forested areas in the NCCSC domain. The basis of this approach is climate envelope modeling, which quantifies the climate conditions where a species is currently present and projects the locations of these climate conditions under future scenarios (Huntley et al. 1995, Guisan and Thuiller 2005, Berry et al. 2002, Loarie et al. 2008, Serra-Diaz et al. 2013). This ‘‘bioclimatic envelope’’ approach describes the conditions under which populations of a species persist in the presence of other biota as well as climatic constraints. Possible future distributions are projected on the assumption that current envelopes reflect species’ environmental preferences, which will be retained under climate change. While this approach does not predict where a species will occur in the future (Pearson et al. 2003, Thomas et al. 2004), it does project one foundational filter of where a species could exist in the future: climate suitability (Thuiller et al. 2005, Serra-Diaz et al. 2013). Consequently, climate niche modeling approaches have widely used to assess change in the location of suitable climates for species under future climate scenarios. We have elaborate on this approach by adding soil and landform to the list of biophysical predictors and thus refer to the approach as species distribution modeling.

The methodology is described in detail in Chang et al. 2014 and Piekielek et al. in review. These methods are summarized as follows.

- Derive locations of species presence from Forest Inventory and Analysis data.
- Derive predictor data related to climate, water-balance, and soils, and topography at an 800-m kilometer spatial resolution. Obtain monthly average temperature and precipitation from the gridded PRISM database (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu).
- Water balance metrics will be derived from PRISM data using a dynamic water-balance (WB) model following Lutz et al. (2010). The model accumulates snowpack and soil water and consumed moisture (or released it as runoff) as a result of approximated rates of evapo transpiration based on temperature with adjustments for slope and aspect.
- Climate and WB predictors will be summarized monthly, seasonally (a five month growing season from May through September), and annually and reported as 30 year climate averages. Climate and WB predictors will also be summarized for the wettest and driest, as well as warmest and coldest annual quarters. Quarters are three month intervals (e.g., DJF) and those with the highest and lowest average quarterly temperature and

precipitation will be included as predictor variables in the models.

- To project future habitat suitability a subset of global climate models (GCMs) that outperform well in the region will be used. For each GCM, we will use a high (8.5) and low (4.5) representative concentration pathway (RCP) to bracket potential future human economic, conservation, and greenhouse gas emissions scenarios. Downscaling to a 1-kilometer resolution was done according to the methods detailed in Thrasher et al. (2013).
- We will use the Software for Assisted Habitat Modeling (SAHM) (Morrisette et al. 2013) and MARS methods (Leathwick et al. 2006) to build SDMs. MARS fit piecewise non-linear basis functions across multiple breakpoints (i.e. knot points) in an intentionally overfit forward stepwise manner and then prunes these based on their contribution to the model. In this way, MARS can both capture the typically non-linear unimodal relationship between species probability of presence and environmental factors and eliminate predictors that do not contribute to explaining species response.
- Models will be evaluated using standard diagnostics in SAHM.
- These methods will be applied to all common tree species and to sagebrush.
- The selected models will be used to first mapped projected presence of suitable habitat conditions for each species and time period. In order to illustrate the trajectory of change climate suitability, we will map for each species the locations of suitable climates for each species and time period and distinguish locations where climate suitability during the reference period was retained vs lost in the future projections. We will then summarize the aerial extent of suitable climate during the reference period, loss of reference–period suitable climate in future periods, and gain in suitable climate in future periods. For newly suitable habitats, we will distinguished between those near enough to currently suitable habits to have some probability of colonization from those more distant from potential source areas.

The 800-m resolution of the analysis is, in our assessment, an appropriate compromise between accuracy of climate projections and ecological relevance to forest species and grasslands. While 800-m resolution is coarse relative to some relevant ecological processes and patterns (Dobrowski 2010), this resolution is fine relative to the ability of climate scientists to replicate actual climates across complex landscapes (Franklin et al. 2013). Thus, this resolution is the current state of the art of climate downscaling and a significant improvement over earlier climate downscaling efforts.

Obj.4 Project grassland phenology under IPCC climate scenarios. Changes in the timing and level of grassland productivity may have important consequences for livestock and wildlife forage production, fire dynamics, and habitat suitability for other wildlife species. We will project potential changes in four metrics of grassland phenology under the same climate scenarios described under Obj 3. The metrics are: start of season, end of season, length of growing season, peak production, cumulative growing season production. We will relate climate to phenology using the methods of Yuan et al. (2014). Phenology metrics will be derived from the normalized difference vegetation index (NDVI) Moderate-Resolution Imaging Spectroradiometer (MODIS) for the years 2000 to 2014. MOD09A1 surface reflectance composites (8-day, 500-m) will be obtained from the Land Processes Distributed Active Archive Center (http://lpdaac.usgs.gov). The NDVI time series will be extracted from these image products using the band 1 (red) and band 2 (near-infrared) of the MOD09A1 products. The phenological metrics will be extracted from the NDVI time series using standard steps of data filtering, temporal smoothing, and derivation of metrics. Phenology patterns will be related to PRISM climate variables (monthly precipitation, maximum temperature, minimum temperature, and dew point), soil variables, and landform variables using multiple linear regression analysis with the SAHMS software package. We will then project the phenology metrics under future climate scenarios by inputting into the regression model the climate variables derived for future projections. Temporal trends and spatial patterns in projected phenology will be analyzed using those we developed in the Greater Yellowstone Ecosystem (Piekielek 2012).

Obj.5. Vulnerability assessment. The results of objectives 1-4 will be used in a vulnerability assessment of vegetation habitat suitability and phenology under climate and land use change. The methods of Hansen and Phillips (in press) will be used for the analysis of tree and shrub species habitat suitability. Estimated area of suitable habitat during a 1950-1980 reference period will be considered as representative of the tolerances of tree species prior to the increased rate of climate warming in the mid-1980s. The aerial extent suitable habitat during the reference period will be considered as one measure of vulnerability to extinction. This is consistent with studies showing occupied area is a strong predictor and the vegetation studies demonstrated that actual presence was strongly related to modeled suitability (Pearson 2014). Locations projected to have suitable climate for a species under future climate scenarios will be divided into three classes for the vulnerability analysis. Locations suitable in climate in the reference period and in the 2030-40, 2050-60, and 2070-2090 period are of interest because tree species are likely to be present in these locations now and given the longevity of these tree species, likely to continue to support tree populations into the future. Locations that are projected to become suitable by 2070-2090 and are within 30 km of currently suitable locations will be distinguished because there is a reasonable probability that they will be colonized by the tree species and contribute to the persistence of the population.

Area of suitable habitat will be reduced in cases where natural vegetation cover is projected in the land use modeling to be converted to more intense human land uses. Newly suitable locations beyond the 30-km threshold will be distinguished because they are candidate sites for assisted migration of these tree species. The 30 km threshold comes from conclusions from published studies Iverson et al. 2004, Gray and Hamann (2013). Consistent with Thomas et al. (2011) and Foden et al. (2013), we will assign cardinal variable ranking for each predictor as a basis for comparisons among species and as a way to derive an overall index of vulnerability for a species from the sum of the predictors. Following Young et al. 2011, our cardinal levels will range from Extremely Vulnerable to Not Vulnerable/Increase Likely in recognition that some species are expected to become less vulnerable under climate change. The values for each of these vulnerability elements will be combined into an overall vulnerability score. This vulnerability ranking will be done for each GWS, ecoregion, and the study area.

Vulnerability of grasslands will be assessed based on the phenological projections. Changes of interest include length of growing season, cumulative annual productivity, and the spatial and temporal dynamics of productive patches, using the methods of Piekielek (2012). Each of these factors is relevant to forage availability of livestock and native ungulates. Spatial and temporal dynamics refers to the change in juxtapositioning of green patches across the landscape over the course of the growing season. Higher herbivore densities can be supported if the dynamics of green patches are within the movement capabilities of the herbivores and suitable forage can be obtained over each portion of the growing season. Elk populations in Greater Yellowstone have declined possibly because warming climate has reduced late summer green-up patches and constrained energy intake by lactating females (Middleton et al 2012). Within ecoregions and GWS, we will rank grassland vulnerability to climate change based on the extend if increase or decrease in length of growing season, cumulative growing season productivity, and connectivity of green patches across these areas across the course of the growing season.

Integrations / synergies with related NCCSC projects

Collaboration Strategies
The foundational proposals present an integrated approach to support the development of the NC-CSC ReVAMP. Here we discuss the strategies that we propose to support the collaboration amongst our teams and with the larger efforts of the North Central Climate Science Center.

Domain-wide
At the scale of the NCCSC, the Climate and Impacts teams will collaborate to depict the major patterns in climate change and drought and the response of vegetation to this change. These analyses will identify geographic locations that are undergoing particular manifestations of climate change and drought and the projected responses of forest composition and grassland phenology to these climate changes. This CSC-wide assessment of change will provide a context for the development of locally-relevant adaptation strategies.

Drought Case Study Intensive (Interaction among the foundational science areas):
Lead by the work of the Adaptation team, the foundational teams will also collaborate on three specific drought-theme cases. These locations for these cases are chosen based on the work of the adaptation and vulnerability team in the DRAI assessments:

- Northwest Colorado DRAI study area
- SW South Dakota DRAI study area
- Wind River Indian Reservation, Wyoming DRAI study area

The Impacts and Climate teams may be involved in the case studies through a) expert participation b) dataset and methodological development c) interpretation of climate and ecological science. The primary foci for ecosystems impacts work will be on forest and grassland ecosystem types. Ecological drought impacts and vulnerability will be investigated through connectivity, and other geospatial ecological measures.

The climatic drivers, past history, and potential future scenarios of drought, along with supporting datasets of climate variables and/or drought indicators considered. The goal of the integrated work is to develop clear, consistent, data-supported drought scenarios that communicate the nature of future ecologically significant droughts effectively with managers, and to iterate with managers to improve the use of this information in planning and adaptation efforts.

Interaction of Foundational areas with other NC-CSC funded projects:
The foundational science will also interact as needed with other NC-CSC funded projects. For example the climate team assisting projects in the use and interpretation of climate data. The Impacts team will be providing guidance on the use of its regional forest and grasslands studies.

Development of synthesis products
The results of the Climate and Impacts teams research will be synthesized in the form of a vulnerability assessment. Following the framework of Glick et al 2011 and Stein 2014, we will integrate the climate projections and ecosystem and vegetation tolerances to project potential impact of climate change across the CSC. The Adaptation team will use the results of the vulnerability assessment in framing their dialog with stakeholders on the perceived risk of these changes and possible adaptation strategies. In addition to producing publications for scientists, we will describe the nature of past change and projected future change in the forms that are highly accessible to resource managers (e.g., webinars and resource briefs

How we will collaborate

- Virtual meetings using new visual conferencing systems being procured by Prof. Ojima.
- Continued participation (sponsorship) of NCUC monthly science/organization calls.
- Twice-yearly meetings of the three team, their post-docs, and associated scientists for progress review (day 1) and joint work/writing/creative work (day 2).
- Field trips to the several study areas in the North Central region; including the DRAI areas and the primary competitively funded projects. The focus of these field trips is to introduce the scientists, and particularly the postdoctoral and graduate level researchers to the managerial concerns, the climatic and ecosystems in the landscapes where they are interesting.
- Visits to the NC-CSC office, to interact with the NC-CSC ReVAMP team/RAM modeling system. Visitor office space (cubicle) at the NC-CSC to be provided.
- A series of ½ day workshops on selected topics geared toward moving a specific project along – for example on the use of new datasets, or the choice of climate data, and design of experiments, geared for a particular landscape.
- Webinars when new/updated datasets are released and/or synthesis reports published
- Student and post-doctoral retreat for NC-CSC and affiliated researchers.

Deliverables (each will be prepared for publication in peer-reviewed journals)

- Maps and analysis of change in fragmentation of natural cover types across the NC CSC as determined by past and projected land use change.

- Summary of change in key ecosystem processes under historic and projected climate change.

- Projections of change in habitat suitability of tree and shrub species habitat suitability under climate change.

- Analysis of trends in grassland phenology under climate change

- Assessment of vulnerability of tree / shrub species habitat suitability and grassland phenology under climate and land use change.

Schedule

	Year 1		Year 2		Year 3	
Task	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4	Q1-Q2	Q3-Q4
Delineate Greater Wildland Ecosystem boundaries	🟩					
Obtain historic and projected land cover and use maps from USGS	🟩					
Calculate and summarize fragmentation metrics for natural cover types	🟩					
Summarize ecosystem process metrics from the TOPS data set		🟩				
Obtain response and predictor data for vegetation distribution modeling	🟩	🟩	🟩			
Develop and evaluate statistical models relating plant species presence to biophysical predictor variables		🟩	🟩	🟩		
Project vegetation habitat suitability under CMIP-5 climate scenarios			🟩	🟩	🟩	
Analyze projection results by ecoregion and GWE				🟩	🟩	
Obtain and prepare MODIS NDVI data for phenology analysis			🟩	🟩		
Develop and evaluate statistical models relating grassland phenology biophysical predictor variables				🟩	🟩	
Project vegetation phenology under CMIP-5 climate scenarios				🟩	🟩	
Conduct vulnerability assessment of vegetation composition under land use and climate change			🟩	🟩	🟩	
Conduct vulnerability assessment of vegetation phenology under land use and climate change				🟩	🟩	🟩
Summarize all results in forms usable by science and management stakeholders	🟩	🟩	🟩	🟩	🟩	🟩

Literature Cited

Allen, C., et al. 2010. A global overview of drought and heat induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259:660–684.

Bell, D.M., J.B. Bradford and W.K. Lauenroth. 2013. Early indicators of change: divergent climate envelopes between tree life stages imply range shifts in the western United States. Global Ecology and Biogeography. 20, 1441–1451, doi: 10.1111/gcb.12504

Bell, D.M., J.B. Bradford and W.K. Lauenroth. 2014. Mountain landscapes offer few opportunities for high-elevation tree species migration. Global Change Biology 20, 1441–1451, doi: 10.1111/gcb.12504

Berry, P.M., Dawson, T.P., Harrison, P.A. & Pearson, R.G. (2002) Modelling potential impacts of climate change on the bioclimatic envelope of species in Britain and Ireland. Global Ecology and Biogeography, 11, 453–462.

Breshears, D. D., et al. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences USA 102:15144–15148.

Chang, T., A.J. Hansen 2013. Climate Change Brief: Greater Yellowstone Ecosystem. Resource Brief. Montana State University, Bozeman, MT. http://www.montana.edu/lccvp/documents/LCCVP_GYE_ClimateBrief.pdf

Chang, T. A.J. Hansen, N. Piekielek. 2014. Patterns and variability of projected bioclimate habitat for Pinus albicaulis in the Greater Yellowstone Ecosystem. PLOS One. November 05, 2014.

Cole, K.L., K. Ironside, J. Eischeid, G. Gargin, P.B. Duffy, C. Toney. 2011. Past and ongoing shifts in Joshua tree distribution support future modeled range contraction. Ecological Applications, 21(1):137–149

Coops, N.C., R.H. Waring. 2011. Estimating the vulnerability of fifteen tree species under changing climate in Northwest North America. Ecological Modelling. 222(2119-2129).

Despain, D.G. (1990) Yellowstone vegetation: consequences ofenvironment and history in a natural setting. Roberts Reinhart Publishers, Boulder, CO.

Dobrowski, S. Z. 2010. A climatic basis for microrefugia: the influence of terrain on climate. Global Change Biology 17:1022-1035.

Drummond, M.A., R.F. Auch, K.A. Karstensen, K.L. Sayler, J.L. Taylor, T.R. Loveland. 2012. Land change variability and human–environment dynamics in the United States

Foden WB, Butchart SHM, Stuart SN, Vie´ J-C, Akçakaya HR, et al. (2013) Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. PLoS ONE 8(6): e65427. doi:10.1371/journal.pone.0065427

Franklin, J., F. W. Davis, M. Ikegami, A. D. Syphard, L. E. Flint, A. L. Flint, and L. Hannah. 2013. Modeling plant species distributions under future climates: how fine scale do climate projections need to be? Global Change Biology 19:473-483.

Gray, L.K., and A. Hamann. 2013. Tracking suitable habitat for tree populations under climate change in western North America. Climate Change 117:289-303.

Great Plains. 2012. Land Use Policy 29: 710– 723

Gross, J. 2013. Rocky Mountain National park Climate Change Brief. Resource Brief. Montana State University, Bozeman, MT. http://www.montana.edu/lccvp/documents/ROMO_CC_Primer_July_2013.pdf.

Guisan A, Thuiller W (2005) Predicting species distribution: offering more than simple habitat models. Ecology Letters 8: 993–1009. Available: http://www. blackwell-synergy.com/doi/abs/10.1111/j.1461-0248.2005.00792.x.

Hansen, A. J., Piekielek, N., Davis, C., Haas, J., Theobald, D., Gross, J., Monahan, W., Olliff, T., Running, S., 2014. Exposure of U.S. National Parks to land use and climate change 1900-2100, Ecological Applications, 24(3), pp. 484-502.

Hansen, A.J. and L.B. Phillips, 2014. Which tree species and biome types are most vulnerable to climate change in the US Northern Rocky Mountains? Forest Ecology and Management, In press..

Huntley, B., Berry, P.M., Cramer, W. & Mcdonald, A.P. (1995) Modelling present and potential future ranges of some European higher plants using climate response surfaces. Journal of Biogeography, 22, 967–1001.

Iverson LR, Schwartz MW, Prasad AM (2004) How fast and far might tree species migrate in the eastern United States due to climate change? Global Ecology and Biogeography, 13, 209–219.

Joyce, L. A., et al. 2013. Climate change and North American rangelands: assessment of mitigation and adaptation strategies. Rangeland Ecology & Management 66:512–528.

Karl, T.R., J.M. Melillo, T.C. Peterson, (eds.). 2009. Global Climate Change Impacts in the United States, Cambridge University Press.

Leathwick, J. R., et al. (2006). "Comparative performance of generalized additive models and multivariate adaptive regression splines for statistical modelling of species distributions." Ecological Modelling **199**(2): 188-196.

Loarie SR, Carter BE, Hayhoe K, McMahon S, Moe R, et al. (2008) Climate Change and the Future of California's Endemic Flora. PLoS ONE 3(6): e2502. doi:10.1371/journal.pone.0002502

Logan, J.A., W. W. Macfarlane, L. Willcox, 2010. Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem. Ecological Applications 20 (4): 895-902.

Loveland, T. R., Sohl, T. L., Stehman, S. V., Gallant, A. L., Sayler, K. L., & Napton, D. E. (2002). A Strategy for Es g the Rates of Recent United States L---$ Cover Changes. Photogrammetric Engineering & Remote Sensing, *68*(10), 1091-1099.

Lutz, J. A., et al. (2010). "Climatic water deficit, tree species ranges, and climate change in Yosemite National Park." Journal of Biogeography **37**(5): 936-950.

McKinney, D.W., J.H. Pedlar, R.B. Rood, D. Price. 2011. Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models. Global Change Biology (2011) 17, 2720–2730.

Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 148 pp.

Melton, F. In Prep. Projection of ecosystem processes across the Great Northern Landscape Conservation Cooperative using the Terrestrial Observation and Prediction System. EOS.

Middleton, A. D., M. J. Kauffman, D. E. McWhirter, J. G. Cook, R. C. Cook, A. A. Nelson, M. D. Jimenez, and R. W. Klaver. 2013. Animal migration amid shifting patterns of phenology and predation: lessons from a Yellowstone elk herd. Ecology 94:1245–1256. http://dx.doi.org/10.1890/11-2298.1

Monahan WB, Cook T, Melton F, Connor J, Bobowski B. 2013. Forecasting Distributional Responses of Limber Pine to Climate Change at Management-Relevant Scales in Rocky Mountain National Park. PLoS ONE 8(12): e83163. doi:10.1371/journal.pone.0083163

Morisette JT, Jarnevich CS, Holcombe TR, Talbert CB, Ignizio D, et al. (2013) Vistrails sahm: visualization and workow management for species habitat modeling. Ecography 36: 129{135.

Nemani et al. 2009. Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS). Remote Sensing of Environment 113:1497-1509

Pearson RG, Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography 12:

361–371. Available: http://doi.wiley.com/10.1046/j. 1466-822X.2003.00042.x.

Pearson, RG, J.C. Stanton, K.T. Shoemaker, M.E. Aiello-Lammens, P.J. Ersts, N.Horning, D.A. Fordham, C.J. Raxworthy, H. Yeong Ryu, J. McNees, H. R. Akçakaya. 2014. Life history and spatial traits predict extinction risk due to climate change. Nature Climate Change 4:217-221.

Pederson, G. T., et al. (2006). "Long-duration drought variability and impact on ecosystem services: a case study from Glacier National Park, Montana." Earth Interactions 10(4): 1-29.

Pederson, G. T., et al. (2011). "The unusual nature of recent snowpack declines in the North American cordillera." Science 333(6040): 332-335.

Piekielek, N. B. and A. J. Hansen (2012). "Extent of fragmentation of coarse-scale habitats in and around U.S. National Parks." Biological Conservation 155: 13-22.

Piekielek, N., A.J. Hansen, T. Chang. In Review. Projected changes in seasonal water-balance suggest decline in climate suitability for forest species in the Greater Yellowstone Ecosystem. J. Biogeo.

Piekielek, N.B. 2012. Remote sensing grassland phenology in the Greater Yellowstone Ecosystem: biophysical correlates, land use effects and patch dynamics. Ph.D. Dissertation. Montana State University, Bozeman, MT.

H. Wayne Polley, David D. Briske, Jack A. Morgan, Klaus Wolter, Derek W. Bailey, and Joel R. Brown. 2013. Climate Change and North American Rangelands: Trends, Projections, and Implications. Rangeland Ecology & Management 66(5):493–51.

Schneider, S.H., S. Semenov, A. Patwardhan, et al. 2007. Assessing key vulnerabilities and the risk from climate change. p. 779–810. In: M.L. Parry et al. (eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Schroeder, M. A., et al. (2004). "Distribution of Sage-Grouse in North America." The Condor 106(2): 363.

Serra-Diaz, J.M., J. Franklin, M. Ninyerola, F.W. Davis, A.D. Syphard, H.M. Regan and M. Ikegami. 2013. Bioclimatic velocity: the pace of species exposure to climate change. Diversity and Distributions 1–12.

Sleeter, B. M., Sohl, T. L., Loveland, T. R., Auch, R. F., Acevedo, W., Drummond, M. A., ... & Stehman, S. V. (2013). Land-cover change in the conterminous United States from 1973 to 2000. Global Environmental Change,*23*(4), 733-748.

Stein, B.A., P. Glick, N. Edelson, and A. Staudt (eds.). 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C.

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, et al. (2004) Extinction risk from climate change. Nature 427: 145–148. Available: http://www.ncbi.nlm.nih.gov/pubmed/14712274.

Thomas, C. D., Hill, J. K., Anderson, B. J., Bailey, S., Beale, C. M., Bradbury, R. B., Bulman, C. R., Crick, H. Q. P., Eigenbrod, F., Griffiths, H. M., Kunin, W. E., Oliver, T. H., Walmsley, C. A., Watts, K., Worsfold, N. T. and Yardley, T. (2011), A framework for assessing threats and benefits to species responding to climate change. Methods in Ecology and Evolution, 2: 125–142. doi: 10.1111/j.2041-210X.2010.00065.x

Thrasher B, Xiong J, Wang W, Melton F, Michaelis A, et al. (2013) Downscaled climate projections suitable for resource management. Eos, Transactions American Geophysical Union 94: 321–323.

Thuiller,W., Lavorel, S., Araújo, M. B., Sykes, M. T. & Prentice, I. C. 2005. Climate change threats to plant diversity in Europe. Proc. Natl Acad. Sci. 102, 82458250.

Wade, A. A., & Theobald, D. M. (2010). Residential development encroachment on US protected areas. *Conservation Biology*, *24*(1), 151-161

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943.

Young, B., E. Byers, K. Gravuer, K. Hall, G. Hammerson, A. Redder. 2011. Guidelines for Using the NatureServe Climate Change Vulnerability Index. Release 2.1. NatureServe, Arlington, VA.

Yuan, F., C. Wang & M. Mitchell. 2014. Spatial patterns of land surface phenology relative to monthly climate variations: US Great Plains, GIScience & Remote Sensing, 51:1, 30-50.