CONSERVING CALIFORNIA'S KLAMATH-CASCADE USING SPATIAL CLIMATE PROJECTIONS

by

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THE PHYSICAL LANDSCAPE

The Klamath-Cascade

Between California's northern border and the Central Valley, the Klamath Mountains meet the Cascades. A relatively unpopulated corner of the state, only a handful of towns and rural dwellings occupy open valley floors. Forested slopes are managed as highly productive timber lands. Mountain peaks are scattered among forests and high elevation wet meadows. Towering Mount Shasta (14,180') dominates the landscape with its granite and glaciers. A majority of the land is in private ownership, but significant tracts are managed by public entities.

Forests

The forests of the Klamath-Cascade are diverse and productive. Most of the forests are dominated by conifer species – Douglas-fir (*Psedotsuga menziesii*), incense cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), and mountain hemlock (*Tsuga mertensiana*) – but there are also stretches of open oak woodland. Forest types range from montane hardwood to Sierran mixed conifer. The Klamath Mountains have some of the most diverse temperate forests in the world (Olson et al. 2001) with some of the species having wide ranges, while others are local specialists such as Shasta red fir (*Abies magnifica shastensis*) and Brewer spruce (*Picea breweriana*).

The vast forested landscape culminates in the Klamath-Cascade being a significant region for timber production. For well over a century the forests have fed sawmills and driven local economies. Today, the region produces nearly a third of California's harvested timber (CA BOE 2014) and provisions several local sawmills and forest product processing facilities.

Water

The Klamath-Cascade is an essential resource for California's water needs. At the south of the region, a large capacity reservoir sprawls at the confluence of the Pit, McCloud and Sacramento Rivers. Water stored in Shasta Reservoir is delivered hundreds of miles farther south for use by agriculture and municipalities. Most precipitation falls in the winter months, and is stored in wet meadows and frozen snowpack until spring run-off. The healthy forested watersheds of the Klamath-Cascade influences the quality of water used by millions.

The abundance of pristine watershed habitat also boast habitat for iconic native fish. The Klamath River and its tributaries are home to one of the largest Chinook (*Oncorhynchus tshawytscha*) and Coho Salmon (*Oncorhynchus kisutch*) runs on the west coast. In the shadow of Mount Shasta, the McCloud River drainage has an endemic fish species, the McCloud Redband Trout (*Oncorhynchus mykiss ssp.*) which has been the focus of extensive conservation activities limiting displacement by introduced fish species and reversing habitat loss (USFS 1998). Playing a critical role, forests shade the steams and slowly release stored water.

Biologic diversity

The Klamath-Cascade is home to exceptional biodiversity (Coleman and Kruckeberg 1999). There are estimated to be over a thousand plant species within the region. A center for converging ecoregions, portions of the Klamath-Cascade have been identified as essential habitat connections for wildlife migration between protected areas (Spencer et al. 2010). Mature forests, with trees hundreds of years old, shelter wildlife such as Pacific fisher (*Martes pennant pacifica*), northern spotted owl (*Strix occidentalis caurina*), American pine marten (*Martes americana*), and sometimes a gray wolf (*Canus lupus*) known as OR-7. These animals require expanses of old, undisturbed forests with complex stand structure. Due to the loss of mature forest habitat, northern spotted owls are federally protected by the federal Endangered Species Act. Policy around northern spotted owls' protected status has shaped forest use for two decades.

The Pacific Forest Trust

For over 20 years, the Pacific Forest Trust has conserved forests throughout the western states, including tens of thousands of acres within the Klamath-Cascade. Often using working forest conservation easements, the Pacific Forest Trust purchases, and then retires, the legal right to develop or subdivide a parcel. This commits the land to sustainable forest use and wildlife habitat in perpetuity.

In a recent prioritization exercise, the Pacific Forest Trust selected the Klamath-Cascade as a focal area. The process identified the 3.1 million acres (Figure 1) for forest conservation, carefully considering current ecological and economic values within the landscape. It also incorporated concepts pertinent to landscape connectivity, forest health, existing protected lands, and climate adaptation (Best 2013).

This project builds on Pacific Forest Trust's existing conservation plan. It considers future climate change and the impacts on tree species composition and habitat for the northern spotted owl. The dilemma the Pacific Forest Trust faces when selecting projects inspired this inquiry. Resources are limited and ideal conservation efforts are focused and prioritized. The selection process benefits from consideration of the forests and their future changes. Understanding potential impacts from climate change, conservation projects can strategically focus on ways to be effective in the long run.

Project Objectives

The objective of this project is to support climate-smart conservation in the Klamath-Cascade through a spatially explicit analysis. The analysis searches for areas which are the best bet for successful forest conservation in an uncertain future. It seeks to make pertinent information available for climate adaptation actions in northern California. In particular, the project looks at climate variability, tree species composition, and northern spotted owl habitat. It uses existing climate data and species envelope models to understand the long-term durability of the Klamath-Cascade's ecosystems. Within the region, it is likely that areas with smaller magnitudes of change will have future climatic conditions more favorable to species persistence. Consequently, these areas are desirable for long-term conservation. This quantitative case study seeks to elucidate understanding vulnerability, uncertainty, and trends for future change in the Klamath-Cascade.

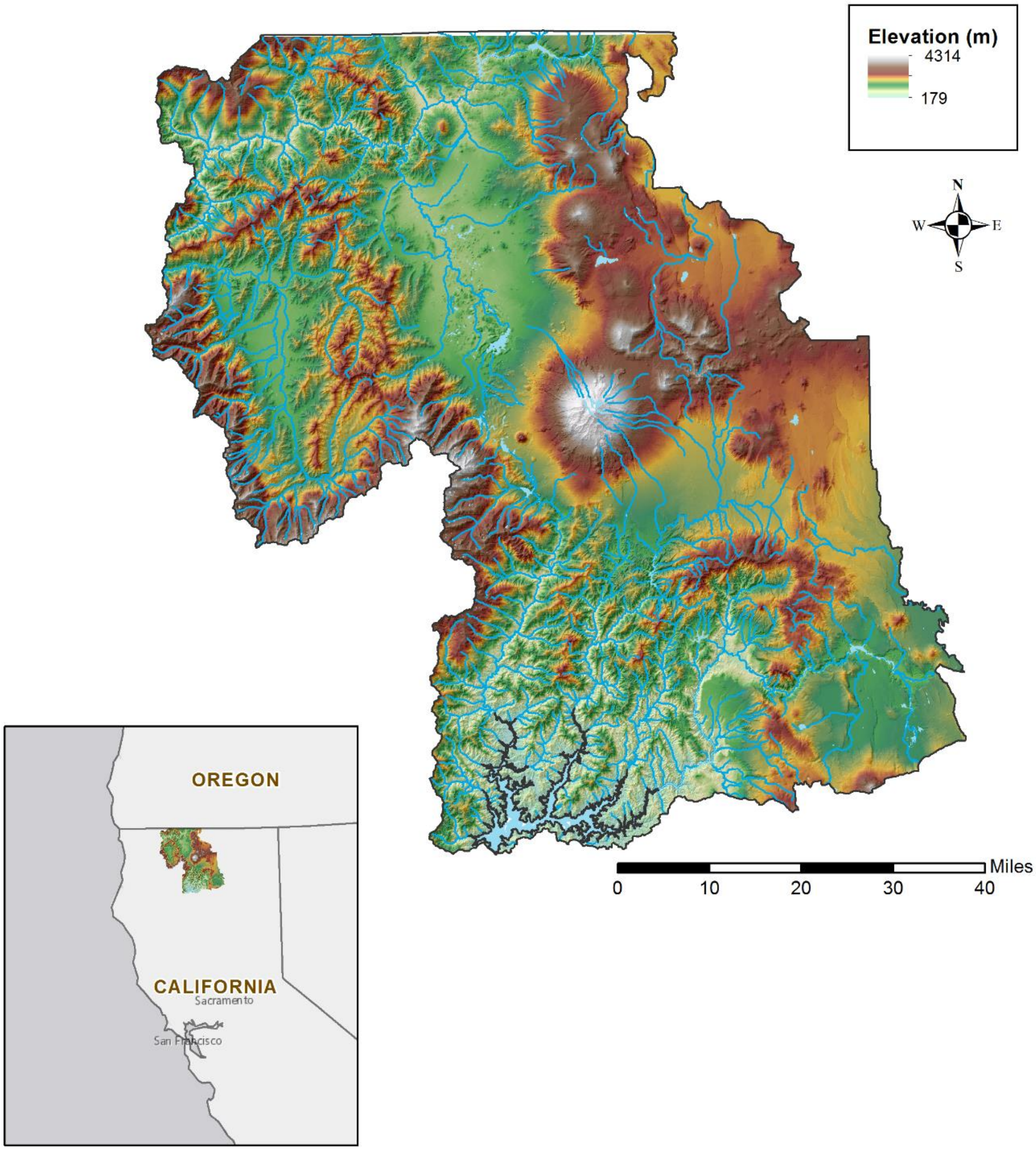

Figure 1: The Klamath-Cascade Region in northern California.

At the center of the Klamath-Cascade, Mount Shasta stands 14,180’ above sea level. The region encompasses 3.1 million acres, two-thirds of it forested, within Shasta and Siskiyou Counties in northern California. The large capacity reservoir provides water for municipalities and agriculture farther south. Natural resource management in the Klamath-Cascade effect ecological and human communities.

THE CONCEPTUAL LANDSCAPE

Climate Adaptation

With proper foresight, organizations can work toward a conservation vision at a landscape scale (Amundsen 2011). Today's actions shape the future of protected lands. However, ecosystems are facing an onslaught of changes – from invasive species to climate – and the full extent of the impacts are unknown. A critical question is whether or not protected areas will be able to withstand the assault (Zavaleta and Chapin 2010). To be effective into the future, conservation efforts need to consider potential global change impacts and the ability of plants and animals to adapt.

Given the current amount of emitted carbon, some level of impact from the changing climate is considered inevitable. Atmospheric levels of carbon dioxide are increasing at an unprecedented rate and temperatures are rising globally (IPCC 2014), intensifying the need to respond through mitigation and adaptation (Yohe and Strezepek 2007). Mitigation consists of actions which reduce the amount of change, and are generally regulatory or technological. Adaptation is the process of cultivating the ability of social and ecological parts of a system to respond to an external pressure (Nelson et al. 2007). Adaptation processes have allowed systems and species to respond to changes over the millennia, both through long term evolutionary adaptation and in the short term via technology and natural resource policy.

Climate change adaptation specifically focuses on addressing the rate and magnitude of climate impacts on natural and human systems (Stein et al. 2014). Because of the complexity and abundance of variables in play, climate change effects are highly uncertain. Therefore, to frame appropriate responses to climate change, managers often use a risk management approach to assess system vulnerabilities. Through this lens, the likelihood of an event is combined with its consequences. Destruction may be caused by a rare flood or certain slow-rising seas, but both scenarios can lead to substantial negative impacts if unaddressed.

Vulnerability to climate change is often broken up into three distinct dimensions (Glick et al. 2011). These components are exposure, sensitivity, and adaptive capacity. Exposure is the amount of climate change experienced by a species or region. It refers to the rate or magnitude of climate change effects such as altered temperate, precipitation, or extreme events. Sensitivity is the degree to which a species or population will be affected by the changing conditions. It is the responsiveness of the health or persistence of the species to environmental conditions and is a composite of a various factors including life history, habitat preferences, and ecophysiology (Dawson et al. 2011). Together, exposure and sensitivity measure the potential impact. Thus, potential impact to a species is a combination of the amount of change at a location and the species' ability to withstand those changes. The third component of vulnerability, adaptive capacity**,** is the ability of the species or system to cope with climate change with minimal disruption (Dawson et al. 2011). Adaptive capacity includes the intrinsic abilities of the species, such as dispersal or phenotypic plasticity, and external variables that allow adaptation such as natural resource management decisions.

Understanding vulnerability helps make good decisions. It focuses possible adaptation responses and future vulnerabilities. Analyzing vulnerability at an appropriate scale for a project is often the first step in planning for climate adaptation actions (Gross et al. 2014). With a vulnerability assessment in hand, managers can explore ways to reduce climate change impacts. Or managers can consider how various management or climate change scenarios might affect a target species or ecosystem. Many vulnerability assessments evaluate individual species, but landscape indicators have also been used to evaluate entire regions (Klausmeyer et al. 2011).

Portions of the vulnerability equation are inherently uncertain. Due to the vast number of different variables, precise understanding of future impacts for systems are computationally intensive and often unknowable. There will never be complete information about how a system will respond to climate change. Thus, managers and conservationists must manage risk and make decisions with some uncertainty. Some managers follow common, widely-applicable recommendations such as increasing protected area connectivity, addressing other threats, and broadening genetic diversity in restoration (Heller and Zavaleta 2009). However, specifics on how to accomplish climate adaptation at scales appropriate to land management are often unclear in common guidelines (Heller and Zavaleta 2009). Increasingly, managers are using decision making strategies that guide robust climate-smart decisions for natural resources despite inherent uncertainty (Dessai et al. 2009).

Climate Robust Decisions

Managers and scientists can evaluate conservation actions through their robustness. Robustness is the consistency of an outcome across a range of inputs (Parrott and Lange 2014). With a robust solution, the same outcome is applicable to a variety of scenarios. When an action is robust to global change, it is likely be effective even if the internal processes or expected impacts are unknown. Robust control is a methodology for identifying solutions which maintain performance within some acceptable bounds (Anderies et al. 2007). In the scope of this project, bounds are a set number of general circulation models that project climate scenarios to 2090.

The intention posits that climate robust actions will not be impacted or compromised by uncertainty within or between climate change projections. Robust decision making is used in conservation planning and other sectors with uncertainty (Hoffman et al. 2014). The advantages of evaluating climate change actions for climate robustness include clear implementation and defensibility in decision making. Additionally, actions and good decisions do not have to wait for highly accurate climate models to be developed (Dessai et al. 2009).

Climate-Smart Conservation

Recent efforts have synthesized principles for climate-smart conservation. Ways to manage natural resources for climate adaptation were recently outlined in a multi-agency guidebook that encourages their adoption (Stein et al. 2014). Themes from *Climate-Smart Conservation* that are especially pertinent to the Klamath-Cascade are to “act with intentionality” and “to manage for change, not just persistence” (Stein et al. 2014, pg 2). In the Klamath-Cascade, this means that effective, efficient conservation should strategically pursue management objectives that are aligned with potential impacts. It is important to visualize the desired conservation outcomes through goal setting. Choosing appropriate targets requires the best information on future conditions.

Managing natural resources under uncertain conditions is a considerable challenge. Even with incomplete information the concepts of managing for persistence or change have gained traction (Stein et al. 2014; Millar et al 2007). These concepts are useful in aligning management goals with the possible impacts on the ecosystem. Efficient conservation demands that goals are strategically identified. Persistence is the goal of keeping ecological communities as they are, the desired endpoint is an ecosystem which functions and looks similar to the current one.

Managing for change, on the other hand, reflects an understanding that the current ecological system will be unable to continue to exist in a particular location. In this situation, it may be prudent for managers to facilitate the transition of the current natural system to a new, more climatically suitable ecosystem.

Selecting the appropriate approach for managing species and ecosystem is a key decision for managers, and is one which may need to be revisited periodically as climate change progresses and social goals fluctuate.

Managing for Persistence

Resistance

There are a variety of reasons that necessitate management of an area to sustain current ecological condition. If it is important to keep in a particular state, managers are often tasked with forestalling impacts, at least in a portion of the community (Millar et al. 2007). This might entail a battle with pests or diseases that is only feasible on a small scale, or replanting a forest that does not naturally regenerate. If the direction and magnitude of the change is uncertain, fortifying the condition might be the best option despite the fact that resistance tactics are generally delaying inevitable change. In many cases, maintaining vital but fragmented patches may be the best or even the only option for a species with limited available habitat.

Resilience

Resilience focuses on the persistence of relationships in a dynamic system. A resilient system fluctuates, possibly through succession, but maintains relationships. In other words, resilient ecosystems are dynamic within expected boundaries. After a disturbance, a resilient system will eventually return to its previous state. Seedlings sprout in burned forests after a fire, slowly closing in the canopy. If an ecosystem has periodic disturbances or other internal dynamics, it may change dramatically in the short term, but will ultimately return to the desired ecological state. This is often called ecological resilience[1]. In general terms, resilience of a system is its ability to bounce back after a disturbance.

To identify ecosystem resilience, researchers establish a threshold. The threshold dictates the amount of force that a system can withstand before changing conditions. Scientists and managers can explore ways to increase the affinity for a desired state and intervene if the system approaches the transition point. However, thresholds are difficult to quantify and cannot be easily extrapolated (Scheffer and Carpenter

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[1] Here, I'm discussing Holling's ecological resilience (1973) as opposed to engineering resilience or resilience related to learning and adapting (Carpenter et al. 2001). I briefly discuss learning resilience – which I'm using as a synonym for adaptive capacity - later in this section. Multiple definitions of resilience are commonly used in both conservation planning and scientific literature; one paper identified ten distinct ways resilience has been defined (Brand and Jax 2007).

2003). Therefore, despite ecological resilience's theoretical value in land management, its complexity impedes practical use.

In conclusion, there is a mismatch between the conceptual usefulness of resilience and the difficulty of measuring it (Thrush et al. 2009). As a conceptual strategy, the path is straightforward: increase ecological resilience and the system will have a greater attraction to a preferred state and will more easily weather disturbances. However, the ecological threshold often cannot be known, or acted upon, in a meaningful timeframe for natural resource management (Contamin and Ellison 2009).

Resilience & Adaptive Capacity

The capability to learn and adapt is another definition of resilience; adaptive capacity is a common synonym (Carpenter et al. 2001). Increasingly, the conservation and land management community is using resilience to mean capable of responding and adapting to climate change (Anderson et al. 2014; Zavaleta and Chapin 2010) or eschewing the term altogether in planning efforts (Stein et al. 2014). Enhancing the ability of the system to respond to unprecedented events is desirable given the changing environment, and definitions, concepts, and applications are evolving.

Managing for Change

Managing ecosystem change is a site specific endeavor based on an understanding that climate change will disassemble natural systems. In some areas it may be appropriate to allow systems to change on their own. For example, warmer, drier conditions might lead to more frequent wildfires and open savannahs gradually replacing forests. A manager could support this realignment of the ecosystem to new climate conditions by protecting the land even after the ecosystem structure changes and allowing natural processes to occur rather than trying to counter the shift (Hirota et al. 2011). Another tactic for allowing gradual system transformation is keeping the landscape connected for migration corridors or evolutionary adaptation. In some cases, the system will change through incremental system adjustments, while in other cases there may be a more dramatic transformation (Nelson et al. 2007).

Managers can choose to play an active role in ecosystem transformation. Assisted migration facilitates the movement of species to new locations. Many environmental conditions are changing more rapidly than species can disperse (Loarie et al. 2009). To encourage the long term existence of certain ecosystem or species, some argue propagules should be brought to suitable climates (Hewitt et al. 2011). The debate is especially pertinent for long-lived species such as trees, both for species conservation and productive forestry (Williams and Dumroese 2013).

A case study in the Klamath-Cascade

Understanding the vulnerability of the Klamath-Cascade helps conservation decisions to be more likely to enhance the long-term durability of the region's forests. This project seeks to identify the exposure of the Klamath-Cascade to climate change. The exposure of the system is the amount of change, such as changes in temperature and precipitation, which plants and animals are likely to encounter. The Klamath-Cascade will likely experience less change than other regions in California (Klausmeyer et al. 2011) making it a persuasive place to conserve rare ecosystems. Managing for persistence is a preferred strategy for protecting sensitive plants and animals – such as the mature forest dependent northern spotted owl – which may be able to cope with moderate climate change fluctuations.

METHODS

Data

Study Area

To be congruent with conservation efforts, this project uses the focal region defined by the Pacific Forest Trust and obtained from their data manager (Figure 1). The Klamath-Cascade region is just over 3.1 million acres and covers portions of Shasta and Siskiyou Counties in California. Within the region about 1.9 million acres are forested (Figure A5, Appendix, Jin et al. 2013) and most of the area is privately owned (57%) (Figure A6, Appendix, Hewes et al. 2014). Vegetation type, elevation, mean annual temperature and precipitation are heterogeneous throughout the landscape.

Climate Data

This study uses readily available data for climate variables and projections of future conditions. Data were from the Rocky Mountain Research Station (RMRS 2014). Current climate data were obtained from a climate interpolation based on 30 years of data in the Western United States (Rehfeldt et al. 2006). This spline model was also used to downscale future climate variables using three different global circulation models (GCM), scenarios, and time periods. The Hadley Center (HADCM3), Geophysical Fluid Dynamics Laboratory (GFDLCM3), Canadian Center for Climate Modeling and Analysis (CGCM3) GCMs are available and because GCMs can provide different results, I used all three GCMs in my analysis. Similarly, I included all three available time periods, which are averages of 30 years of projections surrounding 2030, 2060, and 2090. Throughout the analyses, I only used the A2 emissions scenario, the development storyline (IPCC 2007). Development patterns and carbon emissions have generally followed the narrative. I included spatial data from all 15 available climate variables in this analysis (Table A1, Appendix). Data were available in grids of 30 arc seconds (~1km x 1km) in ASCII format.

Plant Climate Envelope Models

Researchers from Rocky Mountain Research Station created species models which predict the likelihood of tree species occurrence under current conditions and projected futures. The authors first created range-wide models of climate variables that predict occurrence using Random Forest classification algorithms (Iverson and Prasad 1998; Breiman 2001) and Forest Inventory and Analysis (FIA) plots (Bechtold and Patterson 2005). The range-wide models were run for various climate scenarios using projected future conditions. The outcomes were probabilities for species distribution based on climate envelope models (Crookston et al. 2010).

Of the tree species which have been modeled for western North America, I selected ten for this analysis: white fir (*Abes concolor*), Pacific madrone (*Arbutus menziesii*), knobcone pine (*Pinus attenuata*), jeffrey pine (*Pinus jeffreyi*), sugar pine (*Pinus lambertiana*), ponderosa pine, douglas-fir, Oregon white oak (*Quercus garryana*), valley oak (*Quercus lobata*), and interior live oak (*Quercus wislizeni*). Species were selected to represent a range of habitats and life forms present within the study area during current and projected climates. All ten of the available species are relatively common, several are economically important, serving as umbrella species. Data were available in grids of 30 arc seconds (~1km x 1km) in ASCII format (RSMS 2014).

Mature Forests for Northern Spotted Owl

Areas currently protected for mature forests are identified by late successional reserves (LSR) and northern spotted owl critical habitat. LSRs are areas designed by the Northwest Forest Plan to be managed to sustain mature, coniferous forest (Thomas et al. 2006). LSR boundaries were obtained from the Pacific Forest Trust data manager. Northern spotted owl critical habitat was designated by the US Fish and Wildlife Service to facilitate the recovery of the federally threatened species; the geospatial data was obtained from the US Fish and Wildlife (USFS 2014).

Data Processing

Analyses were conducted in the statistical software R v. 3.1.1 (R Core Team 2014). I used the statistical package “raster” to analyze raster data and create raster outputs (Hijmans 2014). Data preparation and visualization were completed in ArcGIS 10.2.2 (ESRI 2014). All data projections were standardized and transformed for compatible processing: UTM Zone 10, NAD 1983.

Analyses

Climate Variables: Principal Components Analysis

To simplify the climate variables I used a multivariate statistical technique, principal components analysis (PCA). PCA is a type of ordination. Ordination is a family of statistical methods which arrange multi-dimensional data along a smaller number of axes than in the original data set (Gotelli and Ellison 2013). Through an ordination analysis, new variables are created along which the original data are distributed. Ordination is particularly useful because it results in a graphical representation of ecological phenomena that facilitates communication. In particular, PCA creates new variables – principal components (PC) – which are orthogonal and uncorrelated. Observations in the dataset can then be mapped along the new variables. Location in the principal component space indicates environmental similarity. Points closer together in PC space are more similar environmentally than those farther away.

In short, PCA reduces a large number of original, correlated variables to a small number of new, uncorrelated PCs. PCs are ordered based on the amount of variation that they explain, and the first few PCs explain the most variation in the data set, allowing me to compress the 15 climate variables into a manageable few PCs.

I conducted a PCA on current climate variables, and then brought projected environmental variables for future conditions into PC space. From there, I calculated the distance between current PC and projected PC to find the displacement over the time periods in PC space. I calculated the distance in PC space of each of the map's gridded squares. Finally, I displayed these distance values spatially, both as PC values and as the difference from current conditions.

After calculating the PC displacements for all available data, I averaged the results by time period. Therefore, the final output was an average of PC distance as calculated with three GCMs for each time period (Figure A3, Appendix). This averaging process, called ensemble modeling, is used to emphasize congruence between models; it is widely used to model species distribution projections under climate change scenarios (Forrester et al*.* 2013).

Tree Species Occurrence: Bray-Curtis Dissimilarity Index

To understand the change in tree species composition over time, I calculated the Bray-Curtis dissimilarity index. The dissimilarity index is the absence of a species in two compared communities. It assesses the dissimilarity between ecological communities by tracking the change in individual species occupancy. I compared the change between future and current communities using modeled species occurrence probability. By comparing current conditions to future projections, I found the overlap between communities over time. A value of 0 indicates that the communities are identical. An increase in ecological difference is identified through an increasing index value; communities without shared species have a Bray-Curtis index of 1. In between, for example with an index of 0.4, the value means that the communities are 40% dissimilar, 60% of the species composition is shared between the times.

I calculated the Bray-Curtis index for the same square in the map grid between different periods to understand the dissimilarity in ecological communities over time. In essence, I analyzed the similarity between the future tree community and the current tree community at the same place. To obtain more robust outcomes, I calculated the Bray-Curtis Dissimilarity for each combination of time period and GCM and then averaged them to obtain one multi-model ensemble output per time period.

Uncertainty

Using the current principal components variables as bounds, I identified areas of the study which are projected to be beyond the current climate data set in the future. I used the bounds from the current principal component axes to select values from the ensemble-averaged principal components. These areas will be outside of the climate conditions that the Klamath-Cascade currently experiences and range across 2030, 2060, and 2090. In the areas of novel climate, the species envelope models are more uncertain because models were fit to the current data set and may have errors when extrapolating.

Mature Forests for Northern Spotted Owl

The northern spotted owl requires territories of large, mature forests, generally 150-200 years old. Identifying persistent climatically suitable locations will facilitate conservation of appropriate habitat. There are two types of land under federal protection; late successional reserves were designated by the U.S. Northwest Forest Plan and critical habitat was designated by U.S. Fish and Wildlife Service. Both seek to manage and enhance old-growth forest conditions.

Using the two types of protected areas as the climatic bounds for mature forests and northern spotted owl habitat, I identified protected areas in the Klamath-Cascade in principal component space as the mature forest climate envelope. Next, I identified areas which were within the bounds of the climate envelope in projected future conditions. I selected the climate envelopes separately for each GCM. If all three GCMs agreed, I designated it as northern spotted owl climatically suitable habitat. I mapped the selected areas of northern spotted owl suitable habitat. Then, I identified areas where the habitat would persist through the three time periods. The outcome are places in the Klamath-Cascade where suitable conditions for mature forests are most likely to persist through time, making them suitable for climate robust decisions.

RESULTS

Change in Climate

The principal components analysis (PCA) revealed clear sorting of variables. Two principal components (PC) explained 96% of the variance among the 15 environmental variables. The first PC was strongly related to temperature variables and explained most of the variance at 84%, while the second PC captured the remaining variance 12% and was aligned with precipitation variables (Table A1, Appendix). Throughout the project I refer to them as the “temp PC” and the “precip PC” although they are a synthesis of various dimensions of these elements.

Comparing differences between time periods for the PC and mean annual averages underlines the complexity the PC variables capture. For example, the average mean annual temperature change between current conditions and 2060 is anticipated to be 3°C. There will likely be more warming inland to the east, but otherwise the change is a coarse gradient. On the other hand, the “temp” PC captures many dimensions of temperature including average minimum coldest temperature in the coldest month and the length of the frost free period. With the greater information input, there is a higher resolution of variance in PC space (Figure A1, Appendix). In short, PCs are able to capture more climate dimensions. A similar increase of information is seen for the “precip” PC (Figure A2, Appendix). Consequently, the two PCs facilitate the visualization and interpretation of the complexity of climate change.

Mapping the PCs highlights a heterogeneous landscape. Under current conditions, the temp PC ranges across six standard deviations of PC values. In future climate space, there are also wide ranging values (Figure 2). However, there is a consistent shift toward warmer conditions. By 2060, the southern end of the Klamath-Cascade is projected to experience temperatures outside the current range (dark gray in Figure 2). In 2090, areas experiencing new temperatures will expand again; some places as much as two standard deviations beyond current bounds.

The “precip” PC also displays a unidirectional trend across the study area. In the future, there will be less precipitation in the Klamath-Cascade, though the size of the decrease is spatially varied (Figure 3). Currently, the highest amount of annual precipitation falls on Mount Shasta. The least amount of precipitation is received by the valleys in the north. Future climate niche outputs continue the pattern; however, in 2030 a small portion of the area will experience precipitation conditions which were previously beyond the bounds of the study area. Less precipitation will fall in the Klamath-Cascade, although the pattern is spatially complex. Moving forward, in 2060, the region beyond current bounds is projected to expand. By 2090, nearly half of the study area is likely to have a precipitation regime beyond the bounds of the study area (dark gray in Figure 3).

The general circulation models (GCMs) that were used in this analysis make different assumptions about future conditions and processes. Creating an ensemble average of the models is one way to mitigate the differences and uncertainty between models. However, averaging models can sometimes cause further complications if the models project trends in opposite directions. Because there were only three models used in this project and they generally agree on the direction of the change, ensembling the models increases certainty and robustness.

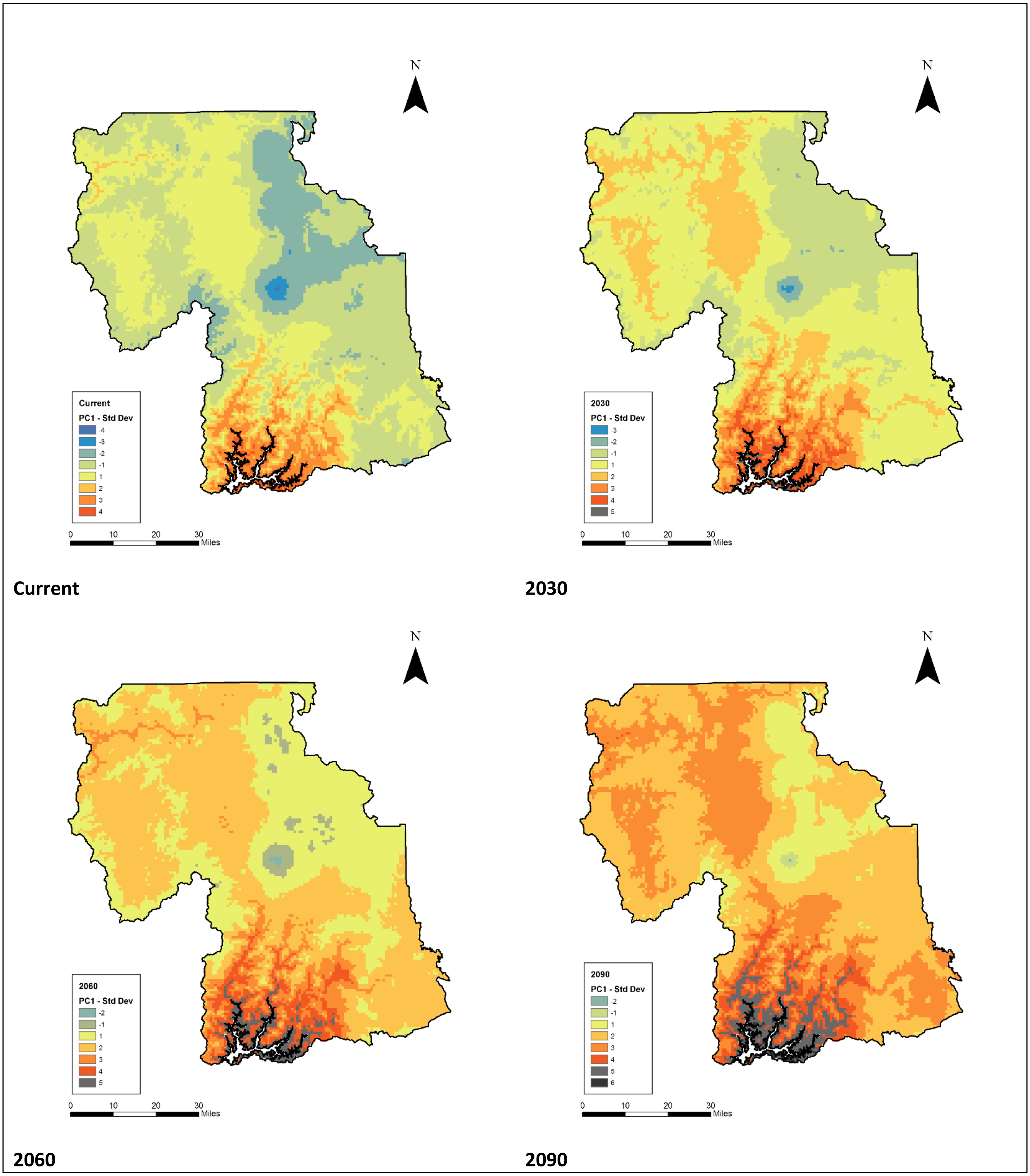
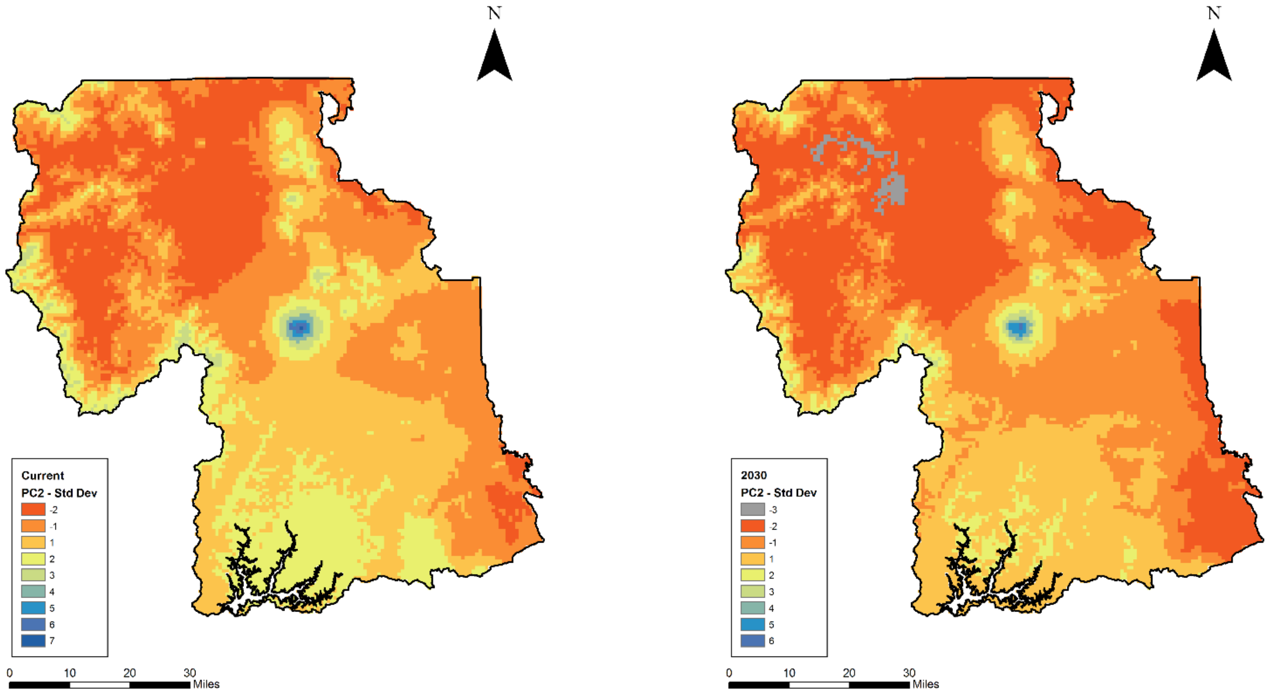


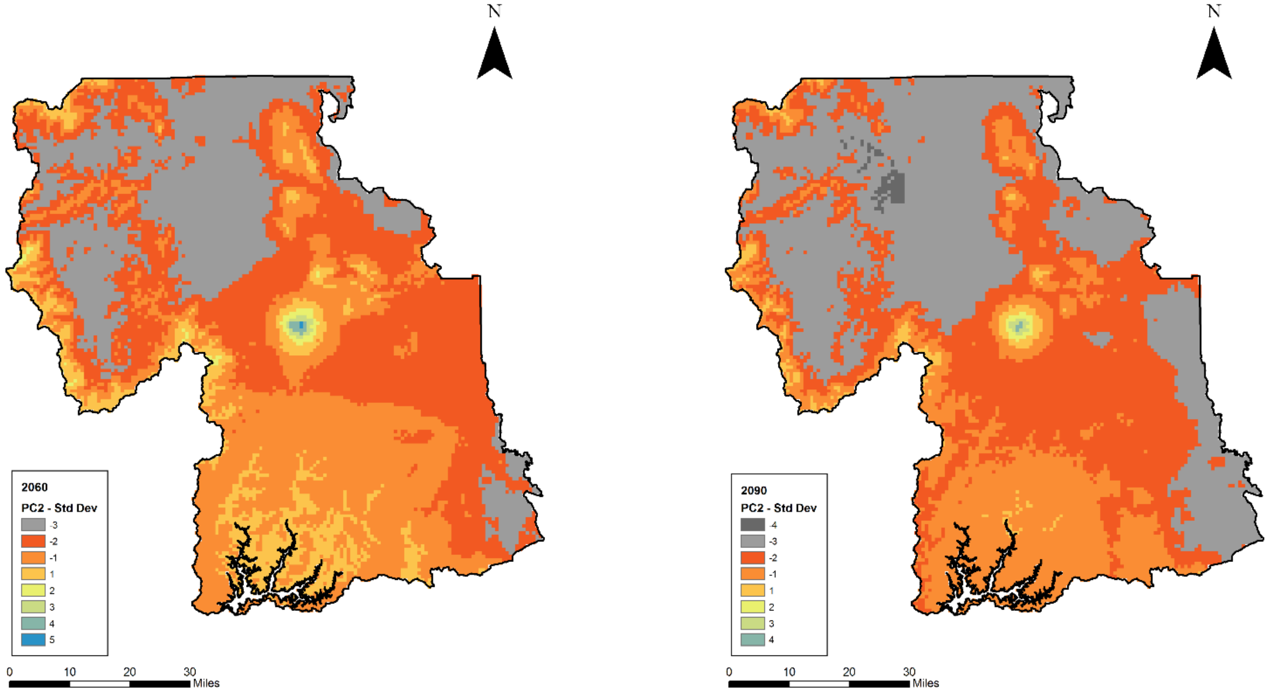
Figure 2. Ensemble-Averaged Principal Component "temp" across the Klamath-Cascade.

Current conditions ranges across six standard deviations. The heterogeneity continues in the future, with a consistent shift toward warmer conditions. By 2060, values will be outside the current range (dark gray) in the southwest.



Current

2030



2060

2090

Figure 3. Ensemble-Averaged Principal Component "precip" across the Klamath-Cascade

Along the precipitation dimension, the Klamath-Cascade will likely have significant regions beyond the current bounds of the data set (gray) beginning in 2030 and expanding to 2090. Conditions will be drier and have less rain and snow.

Tree Species Occurrence: Community Composition

Through the Bray-Curtis dissimilarity index, I found that expected change in species composition varied across the landscape. In general, the southern reaches of the Klamath-Cascade have little expected change in tree species composition and the northern valleys more. However, it is notable that throughout the different scenarios, there are not any areas of complete community turnover. However, the opposite holds true as well; some level of species composition change is expected in all locations (Figure 4). The change between 2030 and current ecological communities are the lowest. A few areas have anticipated changes of less than 10% (dark blue, Figure 4). By 2060, community dissimilarity reaches an index value of 0.5 in many areas of the Klamath-Cascade. In 2090, the northern areas near the Klamath River have the highest dissimilarity value observed, 0.71 (orange, Figure 4). Here, the ecological communities in 2090 are expected to be less than 30% similar to the current ones.

This community dissimilarity index is based on climate envelope models. The models fluidly track the changes in climate suitability. However, they are also limited because they include just a few important environmental dimensions. To be more predictive they could include other relevant variables such as competition, soil properties, connectivity, elevation, vegetation dynamics, and hydrology.

During creation, species models assume that the species currently occupies all possible habitat. In ecological terms, it is an assumption of niche equilibrium. The model seeks to identify the requirements for species and the search for them in the future. Error is present in the models when species do not reach all possible habitat. Random events or disturbances may limit dispersal and occupancy. Biotic pressures like competition or disease may also shape distribution. Possible habitat may be over or under predicted based on model type and parameters.

Different species models have different strengths, including the ability to accurately project beyond the bounds of the dataset. The algorithm used to create the data used in this project, Random Forest, is a bootstrapped classification and regression tree. It has significant advantages, for example; it is robust to over fitting and provides interpretable results (De’ath and Fabricius 2000). However, classification and regression trees do not extrapolate as well as other model types (Elith and Graham 2009). In other words, the species models used in this project have a lower ability to accurately predict when values are beyond the range of the original dataset. Therefore, I considered the values calculated to be uncertain when the climate parameters were beyond the current norms. This uncertainty metric provides a note of caution for the use and interpretation of the community composition change.

The uncertainty of the species composition dissimilarities was assessed by overlaying areas where PC values were out of bounds for the data set. By incorporating this uncertainty from the species envelope models, I found that regions at the southern and northern ends of the Klamath-Cascade should be used with care (Figure 5). The uncertainty is along the “precip” PC in the northern region; in the south, the uncertainty is from the “temp” PC. Because the species niche models are projecting beyond the study area at these locations, the models may be preforming poorly and therefore the dissimilarity analyses may have inherent uncertainty. By understanding this uncertainty, the dissimilarity index can be used with appropriate caution in making conservation decisions.

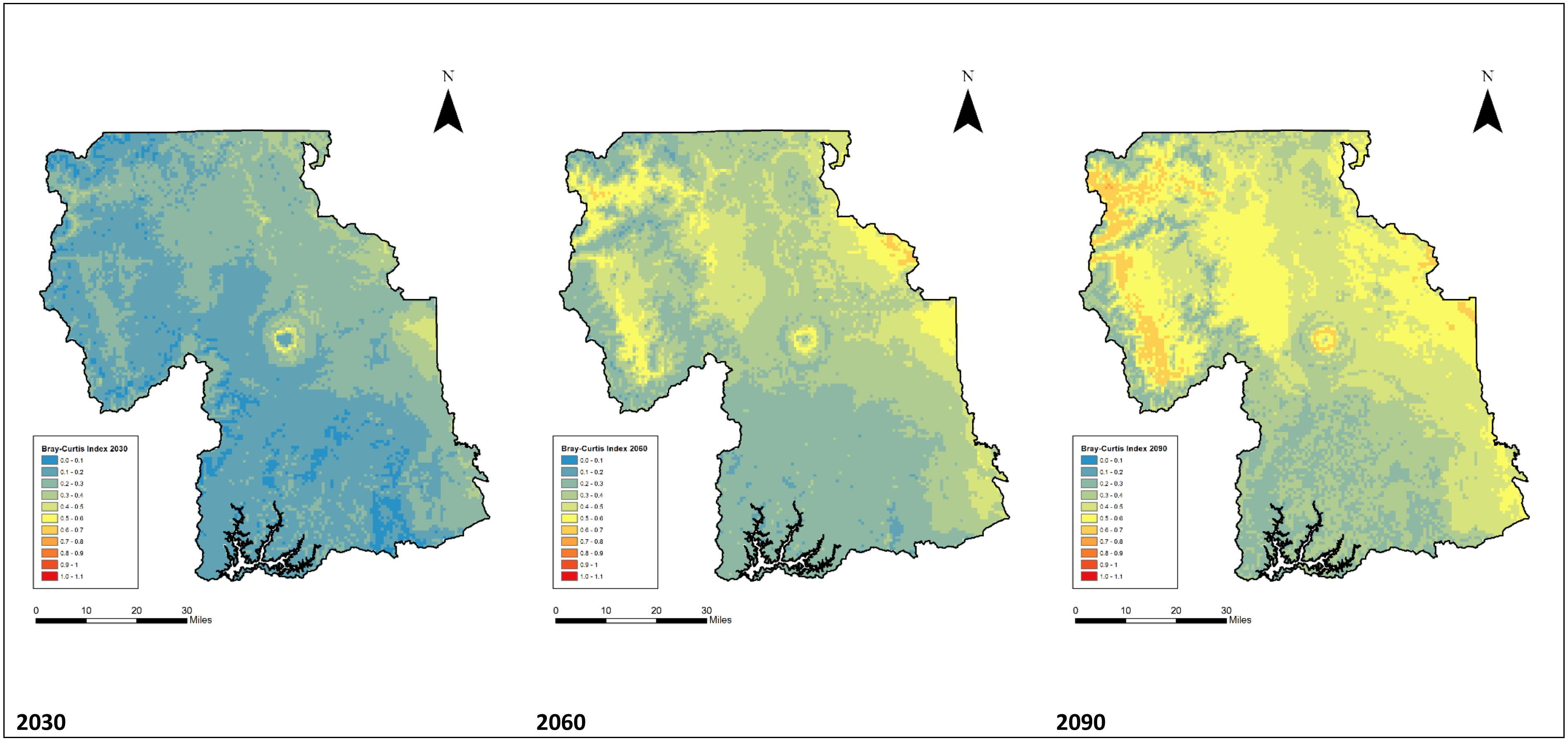


Figure 4. Ensemble-Averaged Bray-Curtis Dissimilarity Index across the Klamath-Cascade.

The dissimilarity index captures the difference between ecological community between current conditions and future conditions (2030, 2060, 2090; left to right). Areas with low dissimilarity are shown in blue; warmer colors indicate higher values and less species overlap. It is notable there are no areas without tree species overlap which would be a value of 1 and shown in red.

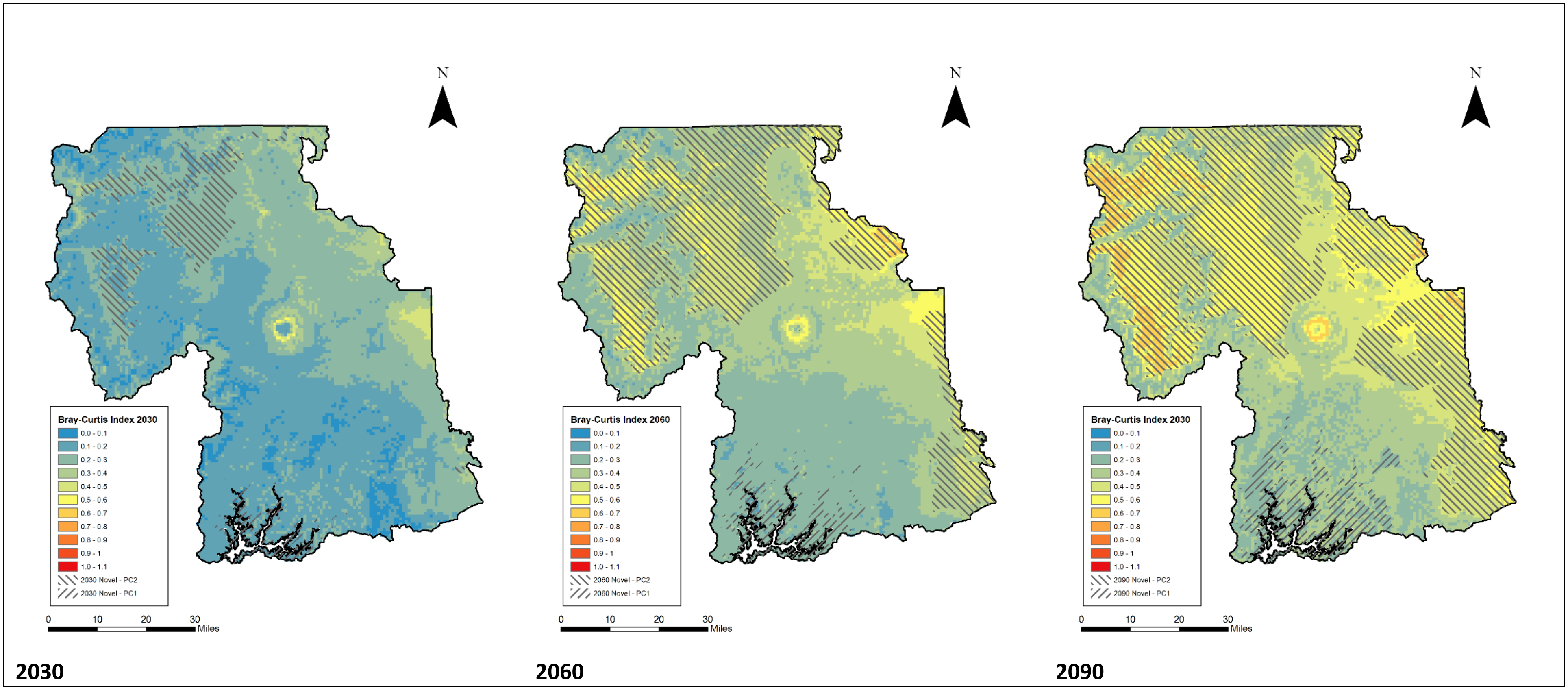


Figure 5. Ensemble-Averaged Bray-Curtis Dissimilarity Index across the Klamath-Cascade with Uncertainty from Climate

Regions of the Klamath-Cascade which will experience climatic conditions beyond the bounds of the current dataset (shading): along the “precip” PC in the northern region and in the south along the “temp” PC. Because Bray-Curtis dissimilarity index was created from models which do not extrapolate beyond the bounds of the dataset well, the index may be preforming poorly in novel climate conditions. This adds uncertainty to the outcome. Original models were created for the western United States (Crookston et al. 2010); however, I take a conservative approach in this project and focus on the regional bounds for the species because species will not uniformly be able to adapt to change (Valladares et al. 2014).

Mature Forests for Northern Spotted Owl

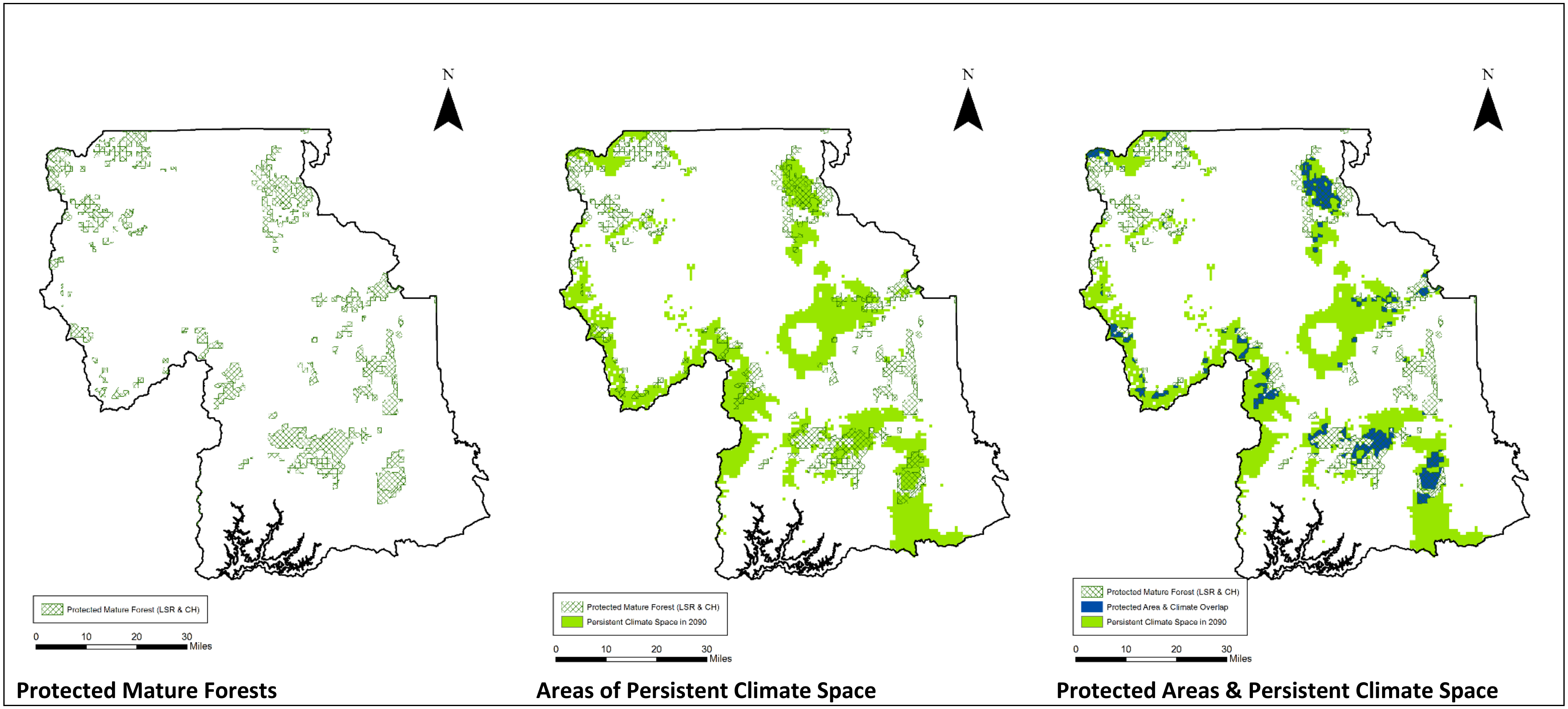
Maintaining mature forests for northern spotted owls is a widespread concern. Federal processes have designated protected areas for mature forests. The areas (late successional reserves and northern spotted owl critical habitat) intend to conserve mature forests and provide habitat for species which need large trees and complex forest structure (Thomas et al. 2006).

Current protected areas occupy over a quarter million acres (285,986 acres). So far, appropriate habitat for northern spotted owls has been limited by fragmentation, disturbance, habitat alteration, and other local influences, but appropriate climate conditions for mature conifer forests are expansive. In contrast, in the future, suitable climate conditions are significantly more restricted. The results of my analysis indicate that over half of the designated protected areas may be beyond the climate bounds of mature forests by the end of the century (Figure 6). These areas will be exposed to warmer and drier conditions beyond what mature forests current experience in the Klamath-Cascade. Some regions, such as those in the northeast will remain climatically suitable habitat over the years (Figure A4, Appendix). Areas which are projected to remain within the appropriate climatic reaches of important northern spotted owl habitat now and in the future (590,144 acres) are places of persistent suitable habitat. However, the overlap between protected areas and projected appropriate climate is limited (99,450 acres).

This analysis is based on the synthesis of climate envelope models, which are snapshots in time. Actual dynamics of species movement and response to climate change will be complex. For example, trees are often long-lived individuals will likely remain in regions which are highly stressful or beyond their ideal climate niche for significant periods of time. Loss of habitat at the trailing edges of ranges, where plant and animals lose available habitat to changing conditions, is expected to proceed more slowly than leading edge range expansions (Urban et al. 1993). On-the-ground, tree species loss may occur more slowly than the climate envelope models project because species might persist in non-preferred climates, or species may have a larger range of acceptable environments than previously understood. Therefore, conservation and management of mature forests and their inhabitants will have to consider a range of processes on different time and spatial scales (Carroll 2010).

Priority Conservation Areas

A robust approach to conservation examines likely outcomes and uncertainties (Kunreuther et al. 2013). In the Klamath-Cascade, this approach suggests managing for species persistence through conservation of places with low magnitudes of ecosystem and climatic change. These areas have lower climate vulnerability due to less climatic exposure. Protecting mature forests for northern spotted owl is regional priority and will necessitate conserving habitat – and young forests that will be future habitat – with low climate exposure. Particularly compelling areas for conservation are places that are consistently within appropriate climate space for mature forest (green, Figure 6) and are adjacent to projected areas that will remain in suitable climate space (blue, Figure 6).



Protected Mature Forests **Areas of Persistent Climate Space** **Protected Areas & Persistent Climate Space**

Figure 6. Federally Protected Mature Forests in the Klamath-Cascade and the Areas of Persistent Climate Space through 2090

Areas projected to remain within the appropriate climatic reaches for mature forests now and in the future (590,144 acres, center) are places of persistent suitable habitat. However, federally protected areas for mature forests (285,986 acres, right) only have limited overlap with projected suitable climate conditions (99,450 acres, left in blue).

DISCUSSION

Change in Climate

The northern reach of California is known for having relatively low climate exposure (Klausmeyer et al. 2011), low historic climate velocity (Dobrwoski et al. 2013), and high natural habitat intactness (Watson et al. 2010). It is thought to provide strongholds and corridors that will give plants and animals options to adapt and persevere to the changing climate (Olson et al. 2012). Therefore, it is a realistic place to search for areas to manage for species persistence. This project found considerable regions with relatively little projected change that are compelling for conservation, especially because many are in private commercial ownership.

Projected future climatic conditions for the Klamath-Cascade are dominated by warmer temperatures and less precipitation. The straightforward PC dimensions identified in the PCA – temperature and precipitation – facilitates the communication of complex projections and their use. However, these dimensions interact. Recent climate modelling included hydrologic processes and calculated how plants might experience those climatic changes (Flint and Flint 2012). The study found that increased temperatures will likely lead to an increase in evapotranspiration and experienced drought, even if precipitation patterns remain at current levels. Thus, change in climate within the Klamath-Cascade will be more complex due to interactions on-the-ground. Conditions and conservation priorities will have to be periodically reassessed.

The scale of this analyses may underestimate local conditions (Hannah et al. 2014). The project used data with a resolution of one kilometer square. Conditions which occur at a smaller scale are not captured. For large forest conservation projects which are thousands of acres in size, a kilometer square (~247 acres) is a realistic measure. However, conditions experienced by plants and animals will be far more diverse due to local environmental and climatic conditions. At a local level, there will likely be more conservation opportunities and areas for species persistence than are projected in this study.

Tree Species Occurrence: Community Composition

Species within an ecological community will respond to changing climate conditions individually (Crookston et al. 2010). Even species in well-developed ecological associations respond to change separately and possibly asynchronously. This project synthesizes individual species movement in order to focus on the ecological community. The calculated species dissimilarity index shows that there will be a shift in tree species communities across the study area, but a complete transformation of the tree community is unlikely. In the northern, lower elevation parts of the Klamath-Cascade, there will be higher levels of dissimilarity between current and future ecological conditions. On the other hand, less dissimilarity is anticipated in the southwest and mountainous regions of the Klamath-Cascade.

Low projected species dissimilarity translates into more certainty that the community will persist in the future. The areas with low species dissimilarity have a lower likelihood that the community composition will change drastically in the coming years. Consequently, areas with little expected change are less vulnerable to climate change and are compelling conservation projects. With low vulnerability, management might assist the persistence of ecological communities. This is likely to be an especially helpful approach for species of high conservation concern with limited available habitat.

In this project, I did not attempt to assess the adaptive capacity of species despite its importance in the climate vulnerability equation. Species may have the genetic capacity to thrive in conditions beyond current habitat; however, it is difficult to model this progression (Valladares et al. 2014). Phenotypic plasticity – the ability of a species to express different traits depending on the environment – is likely to be especially important in face of global change (Hewitt et al. 2011). Species distribution models are generally unable to capture the sensitivity of the species to changing conditions. Similarly, not all individuals within a species may be able to withstand changes in the same way (Lutz et al. 2010). Thus, while species distribution models provide the best available guide, natural communities retain an astonishing ability to surprise.

Further complications in understanding the future of ecological community composition arise in ecological dynamics such as species migration patterns, pests, disturbances, and other stochastic events. The dissimilarity index was calculated on ten tree species, but the Klamath-Cascade region contains nearly a thousand different plant species. Although the selected trees act as umbrella species, the regional biodiversity may respond to the changing climate in ways that are different or asynchronous. In particular, localized or rare species may respond to global changes differently than more common species (Damschen et al. 2010). Over time, species composition change will be influenced by range expansion, as invasive nonnatives and native species shift locations.

Mature Forests for Northern Spotted Owls Habitat

Given the long timescale for these mature forests, which consist of 150-200 year-old trees, forward thinking is essential. Ecosystem development takes a long time and so setting an appropriate trajectory far in advance is necessary. Today's relatively young forests will have time to develop into a mature stand structure that can provide habitat by the end of the century. Because there is an expected loss of appropriate climate space in protected areas, conservation efforts should work to protect areas which will remain within suitable habitat (Carroll 2010). Forests which are directly adjacent to current strategic protected areas are particularly attractive for conservation as many have known northern spotted owl occurrences.

Climate Velocity

While this project is based on four different snapshots in time, global change is occurring continually and at varying rates. There is increasing awareness of the velocity, the direction and magnitude, of climate change. The metric is particularly important in facilitating species conservation and designating protected areas. As species shift their ranges in response to global change, the rate of climate change may too be rapid for species to adapt or move to suitable areas (Loarie et al. 2009). The velocity of climate change will impact the effectiveness of protected areas. As I found for some of the current northern spotted owl protected areas, projected climate changes indicate that some areas will be unable to provide sufficient habitat for species in the future because suitable climate conditions will have moved beyond the designated protected lands.

Topographic complexity in mountainous terrain will likely result in lower temperature climate velocities in mountainous areas (Dobrowski et al. 2013). Change maps in the Klamath-Cascade are consistent with this pattern. However, mountainous regions are particularly susceptible to population isolation. A population may become stranded without any further connectivity to other populations or places to move, fragmented by topographic complexity. Evapotranspiration, temperature, and water available for plants are all affected by climate change in slightly different ways (Dobrowski et al. 2013). Over time, there will be emergent patterns as change shifts dominate processes in different ways (Ordonez and Williams 2013). In the Klamath-Cascade, the heterogeneous velocity may facilitate a rapid expansion of drought-tolerant species such as grey pine (*Pinus sabiniana*) and interior live oak at lower elevations (Serra-Diaz et al. 2014).

Management & Conservation

This case study observes where climate-smart conservation can be prioritized in the Klamath-Cascade region. To accomplish effective conservation, the work must be applied to on-the-ground actions and natural resource decisions. The difficult decision of deciding which places should be managed for change, and which for persistence, still has to be made.

As more regional strategies are developed, it is also important to be aware of the possibility of future surprises like increasing rates of change (Serra-Diaz et al. 2014) or nonlinear responses (Allen and Gunderson 2011). Ecological processes like the invasive barred owl and habitat-altering large fires will impact northern spotted owl conservation. Warmer temperatures may ultimately have a lower impact than increased frequency of large wildfires. Species level adaptive capacity is generally not well understood, but individual responses to stress will shape the forest communities of the future. In order to continually adapt to localized challenges, adaptive management and continual learning could be employed to adjust management responses and, when necessary, reconsider goals (Stein et al. 2014).

CONCLUSION

Climate change will impact the Klamath-Cascade and its ecological communities in complex, heterogeneous ways. Some areas will experience considerably more warming and loss of precipitation than others. The variation in experienced environmental change will propagate throughout the system as ecological communities shift. Just over a third of the areas identified for mature forests protection will remain in suitable climatic conditions in 2090. The mature forests which remain suitable will increase in importance. Additional conservation projects in the areas less vulnerable to climate change will be particularly important in the conservation of old-growth forest species. On the other hand, ecological communities that are projected to transform should be carefully considered, and perhaps places to begin managing for transition and climate realignment. With improving data and understanding, actions will gain specificity with time.

To improve the depth of this project, other aspects of the natural resource management could be examined. The Klamath-Cascade provides many vital ecosystem services: carbon sequestration, drinking water and healthy streams, connectivity for migrating species, and productive forestry. Given that the conservation of biodiversity is just one of many goals for the landscape, assessing climate vulnerability of these dimensions will be an important next step. This project provides a framework for using straightforward, available data to spatially assess projected impacts for climate change. Because many ecosystem services are based on socially expected norms, dissimilarity indices may provide an especially insightful way to plan and communicate likely change. This project provides local conservation efforts with direction for climate-smart actions in the Klamath-Cascade. It bounds uncertainty for climate adaptation actions while staying true to the region's spatial heterogeneity. Intentional, climate-smart actions will provide the best future chance for the Klamath-Cascade's watersheds, forests, and biodiversity.

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I am grateful to the Nicholas School, and the conservation and geospatial communities for inspiration, data, and humor. In particular, I would like to thank the Pacific Forest Trust for hosting me for a summer and providing this compelling conservation question. This project was re-envisioned thanks to the wealth of data that Nicholas Crookston at the Rocky Mountain Research Station directed me to; I am incredibly grateful for his quick responses. My adviser, Dean Urban, patiently provided invaluable insight and guidance for both the statistical analyses and conceptual frameworks. And finally, I could not have completed this long process without the endless loving support of my family and partner; I am deeply thankful to have them in my life.

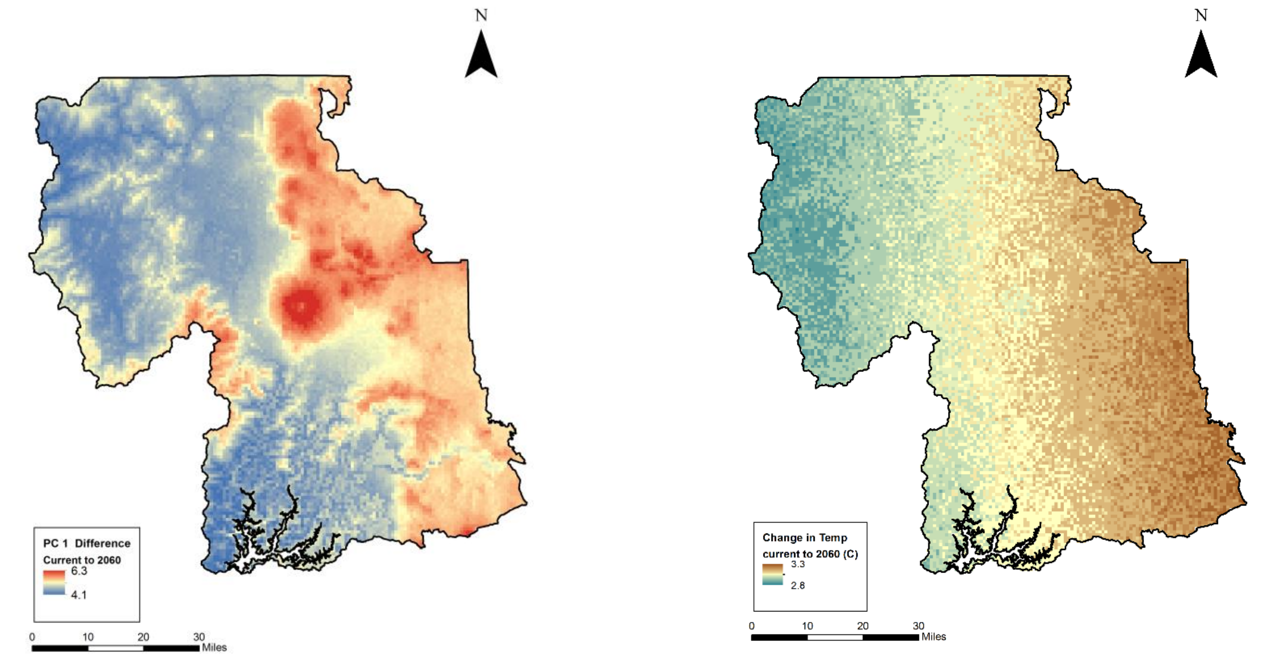
Figure 7. Mount Shasta.

Looking across a forest-meadow system to the towering peak.

APPENDIX

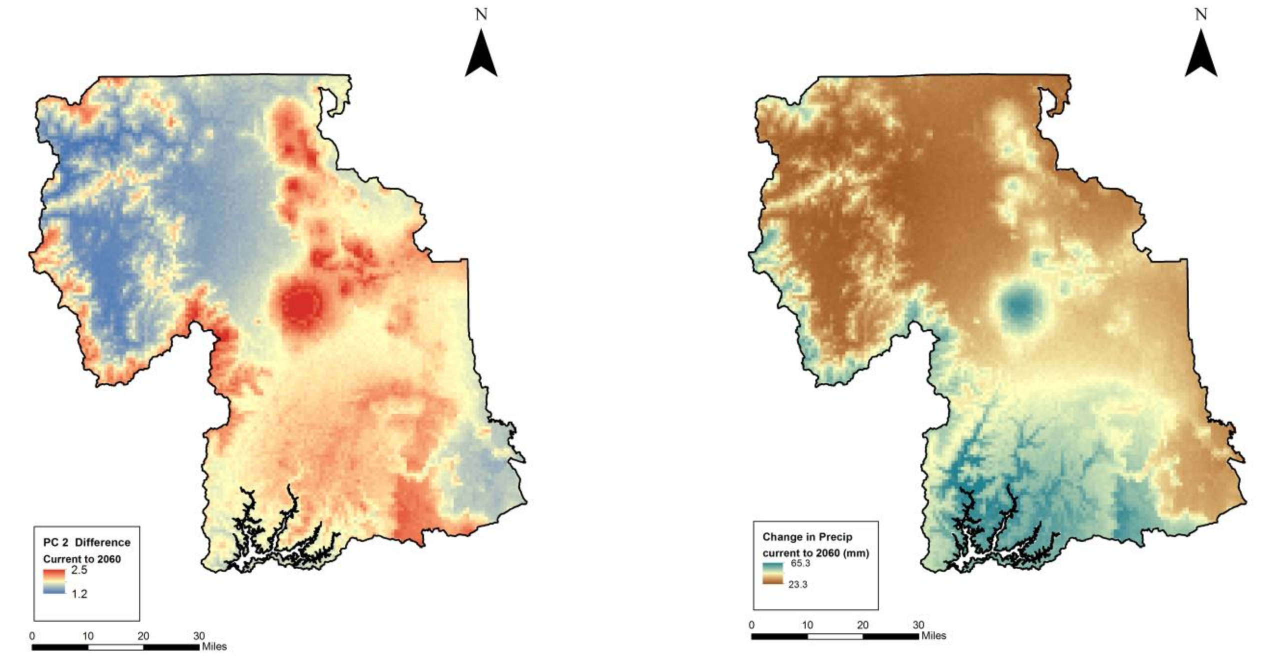
Table A1: Environmental Variables Analyzed & Their Corresponding PCA Loadings

Variable	Variable Code	PC 1	PC2
Julian date the sum of degree-days >5 C reaches 100	d100	-0.275	0.132
Degree-days <0 degrees	dd100	-0.259	0.169
Degree-days >5 degrees C	dd5	0.278	
Julian date of the first freezing date of autumn	fday	0.266	0.120
Length of the frost-free period	ffp	0.277	
Degree-days >5 degrees C within the frost-free period	gsdd5	0.278	
Degree-days >5 degrees C	gsp		0.699
Mean annual precipitation	map	0.169	0.580
Mean annual temperature	mat_tenths	0.278	
Mean annual temperature in the warmest month	mmax_tenths	0.253	-0.252
Mean minimum temperature in the coldest month	mmin_tenths	0.269	
Degree-days <0 degrres C	mmindd0	-0.276	
Mean temperature in the coldest month	mtcm_tenths	0.278	
Mean temperature in the warmest month	mtwm_tenths	0.273	-0.141
Julian date of the last freezing date of spring	sday	-0.27	



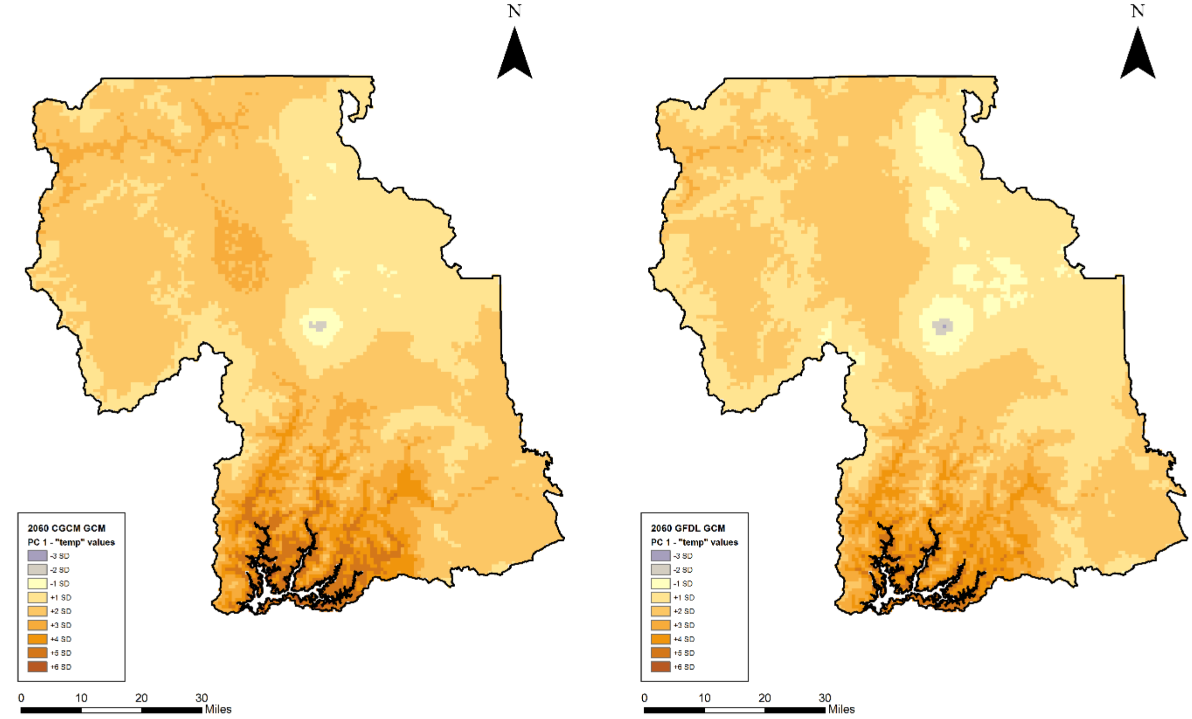
Differences in "temp" PC space. **Differences in mean annual temperature.**

Figure A1. Difference between Current and 2060 conditions for "temp" PC and Mean Annual Temperature

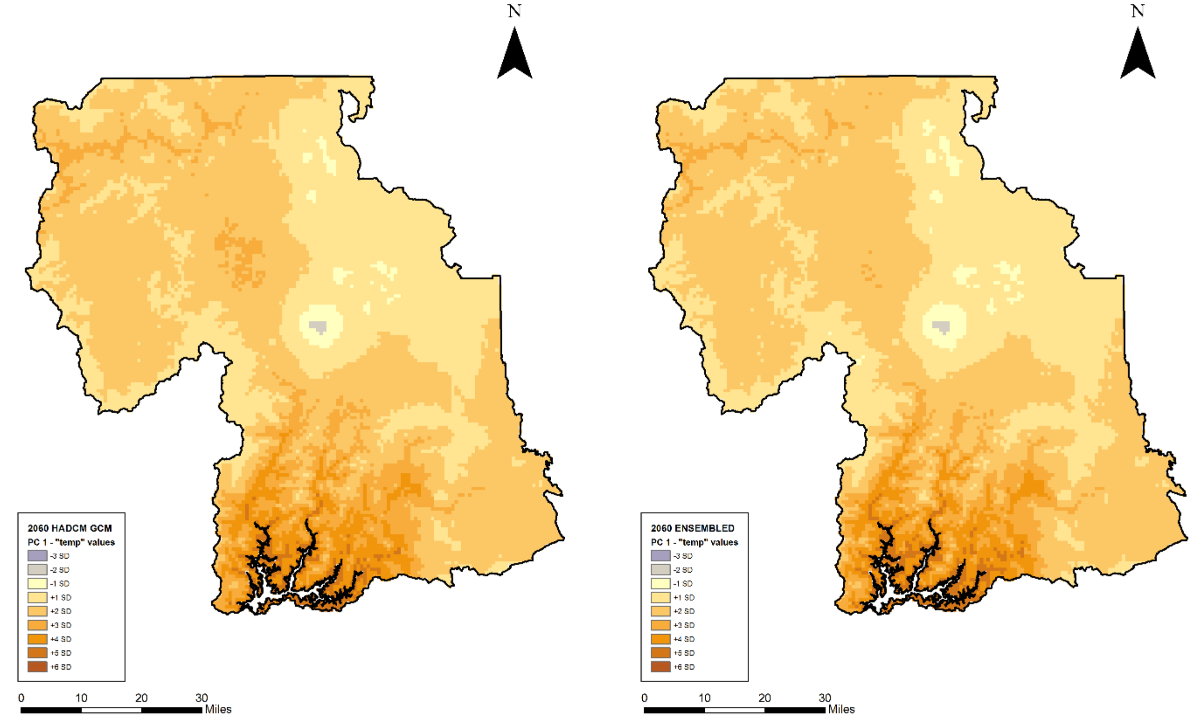


Differences in "precip" PC space. Differences in mean annual precipitation.

Figure A2. Difference between Current and 2060 conditions for "precip" PC and Mean Annual Precipitation

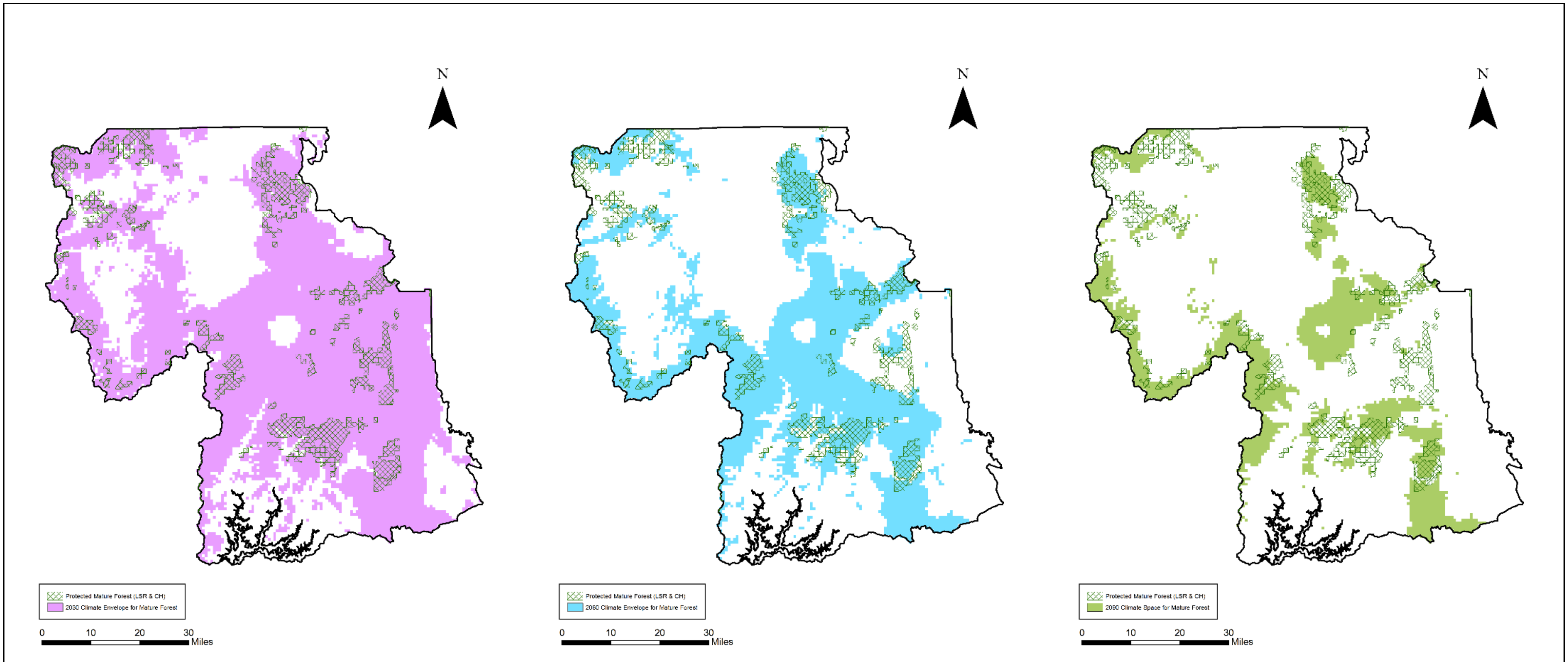


CGCM GCM for 2060 PC1 **GCGM GCM for 2060 PC1**



HADCM GCM for 2060 PC1 **Ensembled Average of 3 GCM for 2060**

Figure A3. Ensemble-Average for the "precip" PC: 3 GCM PC and the final Average (bottom right)



Mature Forest Climate Envelope for 2030

Mature Forest Climate Envelope for 2060

Mature Forest Climate Envelope for 2090

Figure A4. Mature Forest Climate Envelopes for 2030, 2060, 2090. Areas which were consistently within the suitable climate space are identified as persistent habitat (Figure 6).

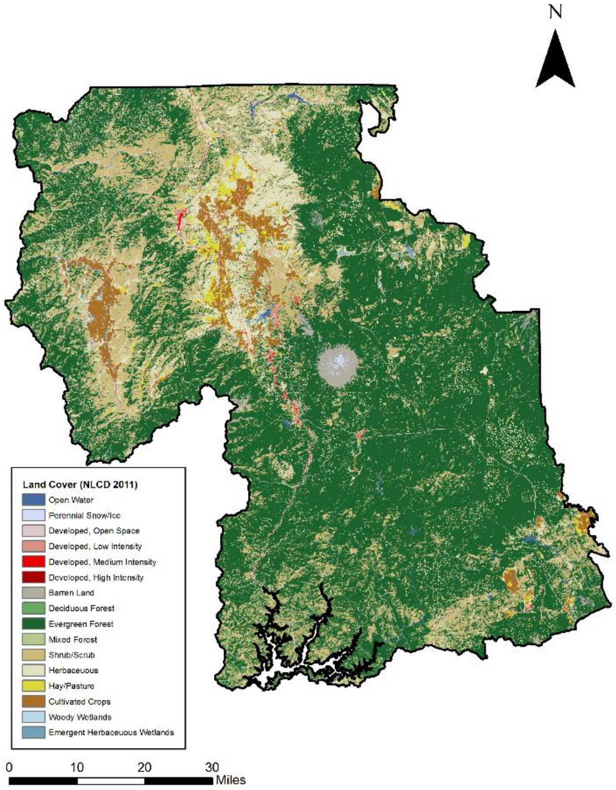


Figure A5. National Land Cover Dataset (Jin et al. 2013)

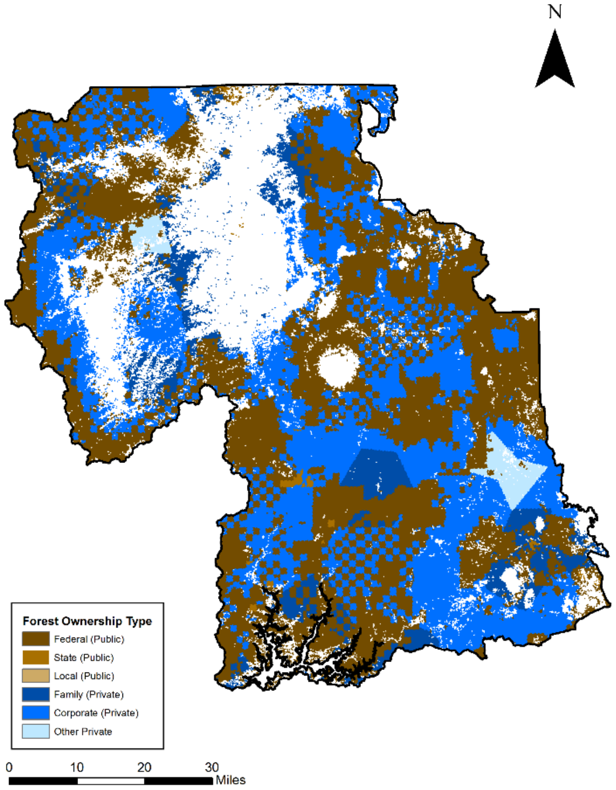


Figure A6. Forest Ownership (Hewes et al. 2014)

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