VEGETATION CLIMATE ADAPTATION PLANNING IN SUPPORT OF THE CUSTER GALLATIN NATIONAL FOREST PLAN REVISION

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ABSTRACT

Global climate change poses substantial challenges to sustaining natural resources on public lands. Fortunately, US federal agencies have made progress on relevant science and climate adaptation approaches. The current challenge is to incorporate this progress into specific natural resource agency plans and management actions. In this report, we assess vulnerability of the portion of the Custer Gallatin National Forest (CGNF) within the Greater Yellowstone Ecosystem (GYE) to climate change and identify potential adaptation strategies that could be incorporated into the forest plan revision of the CGNF. Objectives include:

1. Assess vulnerability to climate change of key ecosystem characteristics within potential vegetation types based on exposure, sensitivity, adaptive capacity.
2. Identify ecological characteristics for which the stated desired condition (based on natural range of variation) is not appropriate given climate change.
3. Identify and evaluate broad adaption strategies and management options for maintaining the ecological integrity of vulnerable vegetation types in the desired condition under climate change.
4. Evaluate the feasibility of these adaptation strategies and management options and prioritize them relative to geographic location, need, effectiveness, and feasibility.

We integrated elements of the Climate Smart Cycle (Stein et al. 2014), the Ecosystem Vulnerability Assessment Approach described by Brandt et al. (2017), and the Northern Rockies Adaptation Partnership (Halofsky et al. 2018) climate framework in our effort to inform the CGNF plan revision. Steps in the project were:

- Review/revise the project approach with the full working team;
- Review best available scientific information for the period 1980-2100 on interactions among climate, land use, ecosystem process, and vegetation;
- Based on this review, assess vulnerability of ecological characteristics of cover types and Potential Vegetation Types (PVTs) types across the CGNF through a consensus approach;
- For vulnerable vegetation types, derive broad adaptation strategies and specific tactics and evaluate feasibility, ecological soundness, and effectiveness.

Our review of current knowledge revealed that the projected rapid changes in climate will impact the vegetation of the GYE in myriad ways both directly by shifts in growth, mortality, and regeneration, and indirectly by changes in disturbance regimes, hydrology, snow dynamics, and exotic invasions. Tree species and PVTs are likely to respond differentially to these changes with some expanding in suitable habitat and others contracting.

In evaluating vulnerability of vegetation cover types within PVTs in the study area, we ranked as most vulnerable Douglas-fir (*Pseudotsuga menziesii*) in the Warm Dry PVT and whitebark pine (*Pinus albicaulis*) in the Cold PVT. Douglas-fir at lower treeline has suffered loss of older, larger individuals in recent decades and habitat suitability models project that it will be replaced by sagebrush/juniper (*Artemisia/ Juniperus)* communities under future climate. Whitebark pine in the GYE has undergone massive mortality by mountain pine beetles (*Dendroctonus ponderosae*) since 2000. Moreover, white pine blister rust (*Cronartium ribicola)* is expected to

cause increasing mortality in whitebark pine and climate suitability for this species for is projected to be reduced dramatically under future climates.

The CGNF currently emphasizes using natural range of variation to set a desired condition to meet the goal of maintaining ecological integrity. This approach has been widely embraced for ecosystems where current conditions do not substantially differ from natural range of variation and managing towards natural range of variation is likely to increase resilience of the ecosystem under future change. We concluded that managing towards natural range of variation is a reasonable approach for the CGNF given the current relatively natural state of the forest ecosystem and projected future change. How to maintain some cover types within this desired condition in the face of changes in climate and disturbance will likely represent a substantial challenge, however.

Three adaptation strategies were recommended:

1. Prevent conversion of Douglas-fir to grassland in the Warm Dry PVT;
2. Maintain large diameter Douglas-fir trees in a savannah setting in the Warm Dry PVT; and
3. Implement the Greater Yellowstone Coordinating Committee whitebark pine strategy in the context of climate change.

Tactics were developed for each strategy and the effectiveness, and implementation potential of each was rated.

This report is intended to inform the CGNF Environmental Impact Statement, the final revised forest plan, the plan implementation strategies, and the design of the monitoring and evaluation approaches. We suggest that the CGNF can likely best meet its forest resource objectives by attempting to anticipate change, planning and managing to maintain ecological resilience in the face of climate change, and embracing adaptive management methods to evaluate and improve success. We offer several considerations and suggestions on how to do this. We close with an evaluation of our approach and suggestions for communication of the results.

INTRODUCTION

The global climate has warmed significantly over the past century as a result of human burning of fossil fuels (IPCC 2013). This changing climate has influenced plants, fish, and wildlife directly based on their temperature and moisture tolerances. It has also altered wildfire, pest outbreaks, storms, and success of invasive species, which in turn influence native species and ecosystems. Natural resource agencies in the United States are now adjusting to incorporate consideration of climate change into planning and management. Climate science and general approaches for agencies to adapt to climate change have been advancing since the US Department of Interior instigated specific programs in 2011: Climate Science Centers and Landscape Conservation Cooperatives (USDI 2009). Knowledge is now available for most regions of the United States on rates of climate change, land use, disturbance, and species responses using methods including field surveys, paleoecology, species distribution models, and simulation models (e.g., USGCRP 2017). The current challenge is to incorporate this progress in science and climate adaptation into specific natural resource agency plans and management actions. In this report, we synthesize available information to assess vulnerability of forests in the Greater Yellowstone Ecosystem (GYE) to climate change, and identify adaptation strategies that could be incorporated into the forest plan revision of the Custer Gallatin National Forest (CGNF) in Montana.

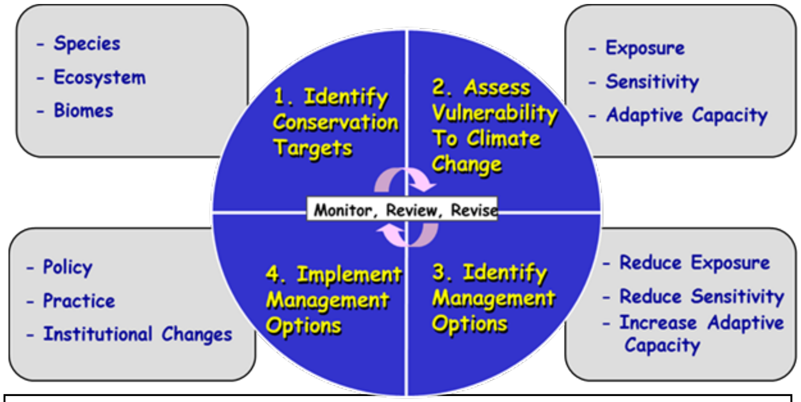

Figure 1. The Climate Smart adaptation cycle embraced by many federal natural resource agencies. From Glick et al. 2011.

The National Park Service, US Fish and Wildlife Service, and the USDA Forest Service have convened programs and activities to develop and assess approaches to better link climate science with natural resource planning and management. The Climate-Smart Conservation approach of the National Fish and Wildlife Federation (Figure 1, Glick et al. 2011, Stein et al. 2014), for example, represents vulnerability as the exposure of a species, community, or process to climate change, sensitivity to this exposure, and capacity to adapt to the change. Each of these elements of vulnerability informs potential management options.

Vulnerability assessment in the context of climate change typically has a high level of uncertainty due to our inability to predict future human behavior and ecological response. Brandt et al. (2017) developed a participatory approach (Figure 2) to evaluate species and ecosystem vulnerability and level of uncertainty based on level of agreement among participants. This is especially useful in the application to federal planning units that are often smaller than the broad geographic areas over which scientific hindcasts and forecasts are typically made.

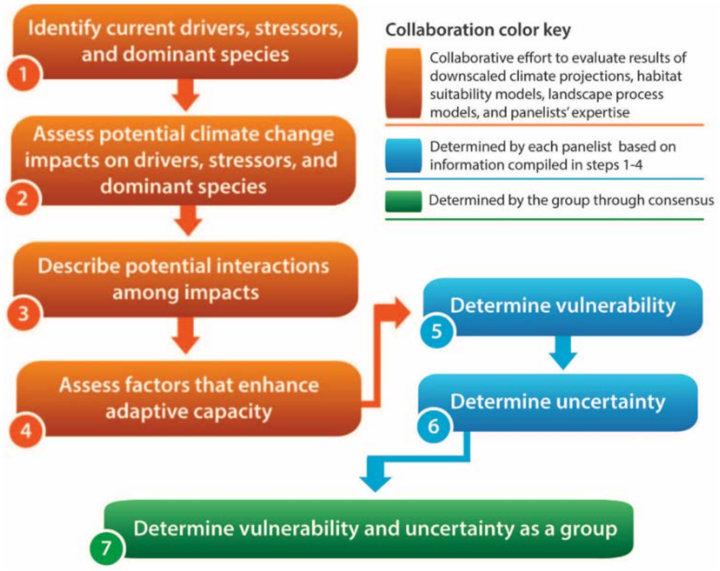

Figure 2. Vulnerability assessment process used in this project. Figure from Brandt et al. (2017).

The USFS Northern Region Adaptation Partnership (NRAP) (Halofsky et al. 2018) built on the Glick et al. (2011) approach. This two-year effort used state-of-science climate change vulnerability assessment and developed adaptation options for large landscapes within in the Northern Rockies region. Resource managers use the assessment to develop a detailed list of ways to address climate change vulnerabilities through management actions. The effort assessed forest vegetation responses to climate, projected climate change, vulnerability of vegetation, adaptation strategies and tactics.

The large number of adaptation strategies and tactics, many of which could be implemented via current management practices, provide a pathway for slowing the rate of deleterious change in resource conditions. The Northern Region of the Forest Service is currently developing a framework by which the NRAP assessment can be used to inform USFS planning and management efforts at the scale of national forests. Thus, the next step in climate adaptation is for national forests, parks, and fish and wildlife refuges to plan for and manage their lands and waters to achieve their objectives under the influence of climate change.

The National Forest Management Act requires national forests to periodically update their management plans. The CGNF is currently in the process of revising its forest plan that will guide the activities of the forest managers for the next 10-15 years or more. Forest plans set the overall management direction and guidance for each of our national forests. Climate change issues have largely emerged since the previous Custer and Gallatin NF plans were enacted in 1986 and 1987, respectively. Our work aimed to provide information useful to revising the forest plan in ways that increase forest resilience under climate change. .

The plan revision is being executed under the Planning Rule established in 2012. In contrast to previous planning rules, the 2012 rule requires forests to develop plans that ensure “ecological integrity”, defined as “the quality or condition of an ecosystem when its dominant ecological characteristics (for example, composition, structure, function, connectivity, and species composition and diversity) occur within the natural range of variation (NRV) and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence.” (36 C.F.R. §219.19). To achieve ecological integrity, the 2012 Planning Rule emphasizes planning for resilience and managing to enhance the ability of ecosystems to adapt to change, stressors and system drivers, including climate change.

The plan has a number of elements, called “plan components” that collectively guide the forest to achieve and sustain ecological integrity. Desired Conditions are fundamental and set the vision for management. These are descriptions of specific characteristics of the plan area, or a portion of the plan area, toward which management of the land and resources should be directed. Other plan components (objectives, standards and guidelines, and suitability), are designed to achieve the Desired Condition. The “management approaches” section of the plan describes the principal strategies and program priorities to carry out projects and activities developed under the plan.

Desired vegetation conditions are stratified by broad potential vegetation type (PVT) (Milburn *et al.*, 2015), a grouping of habitat types (Pfister *et al.*, 1977). The CGNF portion of the GYE consists of approximately 18% “Cold” Forest PVT (e.g. whitebark pine (*Pinus albicaulis*), subalpine fir (*Abies lasiocarpa*), Englemann spruce (*Picea engelmannii*)), 36% “Cool Moist Forest” PVT (e.g. mixed mesic Douglas fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*), and 15% “Warm Dry Forest” PVT (e.g. dry Douglas fir (*Pseudotsuga menziesii*), limber pine (*Pinus flexilis*)). These three PVTs represent the major forest vegetation on the CGNF and are the focus of this report.

The CGNF is basing ecological desired conditions on an analysis of NRV for key ecosystem characteristics (e.g. tree size class, forest density, cover type, species presence, etc.). NRV was estimated using the state-and-transition simulation model SIMulating Patterns and Processes at Landscape ScaLEs (SIMPPLLE) (Chew *et al.*, 2004). Focusing on NRV as a guide for desired conditions is based on two primary assumptions: 1) native biota evolved within the landscape context of a range of variability and thus maintaining NRV should sustain native biodiversity; and 2) NRV conditions will be resilient to many of the stressors associated with climate change including increased intensity and frequency of disturbance. As such, it is assumed that NRV represents, at minimum, a useful waypoint to manage for resilient ecological systems. However, the historical range of variability may prove an insufficient - or even inappropriate - guide under an altered future climate (Millar et al. 2007). Whether a historical range of variability still serves as a target when managing to maintain biodiversity and resilient ecosystems is the focus on much debate in natural resource science (Harris et al. 2006, Keane et al. 2009, Aplet and McKinley 2017, Belote et al. 2017). Consequently, our working group evaluated the applicability of setting Desired Condition as NRV in the GYE study area.

The goal of this report is to assess climate vulnerability of forest vegetation and evaluate management options in support of the CGNF Plan revision. Objectives include:

1. Assess vulnerability to climate change of key ecosystem characteristics within potential vegetation types based on exposure, sensitivity, adaptive capacity.
2. Identify ecological characteristics for which the stated desired condition (based on NRV) is not appropriate given climate change.
3. Identify and evaluate broad adaption strategies and management options for maintaining the ecological integrity of vulnerable vegetation types in the desired condition under climate change.
4. Evaluate the feasibility of these adaptation strategies and management options and prioritize them relative to geographic location, need, effectiveness, and feasibility.

Evaluating, prioritizing, and implementing climate change adaptation strategies and tactics has been, to date, where many efforts have stalled (Olliff et al. 2016.). Halofksy et al. (2015) evaluated climate change adaption efforts within federal agencies from 2013-2014 and cautioned that “Mainstreaming climate-smart practices in federal agencies has been slow to develop”. Lemieux et al. (2013) surveyed managers and found that managers identified lack of well-defined actions at the management scale as a barrier to implementing climate change actions. Archie et al. (2012) found that common barriers to adaptation activities were lack of information at a relevant scale, budget constraints, and lack of specific agency direction.

This effort sidesteps many of those problems. With the 2012 Planning rule, the US Forest Service mandated that climate change be considered in Forest Plan Revisions. During our second workshop, a group of experienced, local scientists and managers identified actions that help meet key goals of the CGNF forest plan in the most vulnerable vegetation types, with information based on analysis at the most local scale available.

METHODS

We integrated elements of the Climate-Smart Conservation Cycle (Stein et al. 2014), the Ecosystem Vulnerability Assessment Approach described by Brandt et al. (2017) and the NRAP (Halofsky et al. 2018) climate framework in our effort to inform the CGNF plan revision. Steps in the project were:

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- For vulnerable vegetation types, derive broad adaptation strategies and specific tactics and evaluate feasibility, ecological soundness, and effectiveness.

The study area is centered on the portion of the CGNF that is within the GYE (Figure 3). The CGNF consists of more than 3 million acres of National Forests System lands in several geographically isolated land units extending from the Montana-Idaho border into South Dakota. For planning purposes, the CGNF has identified five broad geographic areas, two of which are within the GYE and were the focus of this project: the Absaroka Beartooth Mountains and the Madison, Henrys Lake, Gallatin Mountains geographic areas. The GYE portion of the CGNF totals approximately 2 million acres.

Climate and fire in the GYE have undergone phases in recent decades and centuries that provide a context for planning for the future. Thus, the time period most relevant to planning for the coming decades spans back to the mid 1800s. The region has warmed since the end of the Little Ice Age in about 1880 (Whitlock and Bartlein 1993). Early EuroAmerican settlement and subsequent fire management resulted in a fire exclusion period from ca 1880 to 1988 (Littell 2002, Gallant et al. 2003). The huge fires in 1988 broke this low-fire period and fire has been frequent in the GYE since then, including low elevation forest fires (see Results section). Projections for the future indicate warming and increased fire.

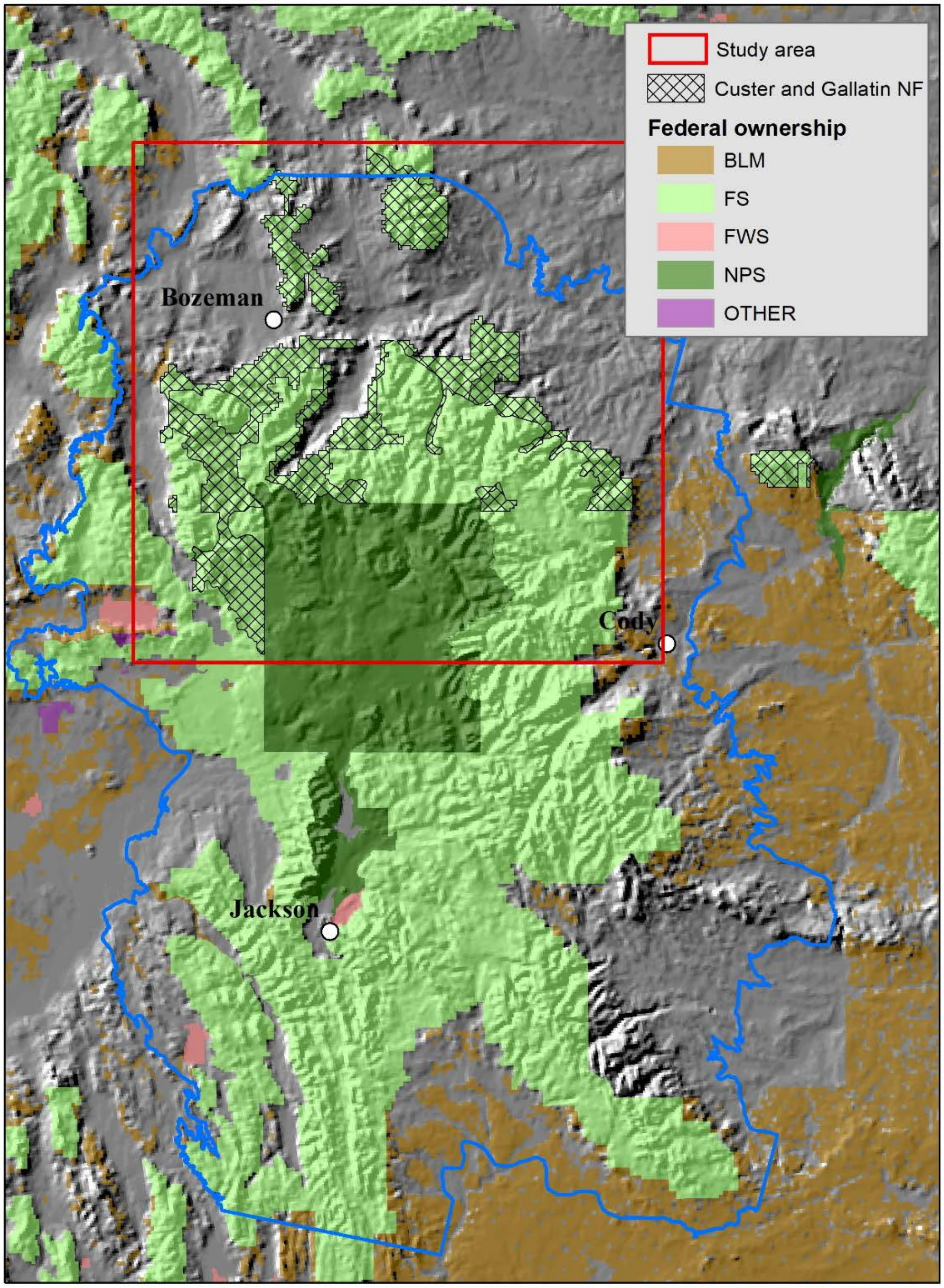

Figure 3. Spatial extent of the project (red polygon).

The project was initiated by assembling a working team with expertise in climate science, ecology, forest planning, resource management, and adaptation planning (Table 1). We conducted an initial teleconference to review and revise our approach and to assemble a list of relevant readings. Participants were instructed to read relevant literature prior to the first workshop to assess vulnerability.

The objectives of the first workshop were to review and synthesize the best available information on interactions among climate, disturbance, and vegetation; and use this synthesis to assess vulnerability of PVTs. Following Glick et al. (2011), vulnerability was defined as the extent to which a conservation target (e.g., species, habitat, or ecosystem) is susceptible to the impacts of climate change. It is the combination of a conservation target's exposure, sensitivity, and adaptive capacity. We sought to identify elements of CGNF are vulnerable, but also why they are vulnerable. Moreover, this workshop focused on assessing the vulnerability of the existing ecosystem, and not what it might be with additional management actions (e.g., restoration or adaptation). To assess vulnerability of vegetation in CGNF, we based the structure of the first workshop on the process described by Brandt et al. (2017, Figure 2). This approach to ecosystem vulnerability assessments has been applied successfully to multiple other forests in the Midwestern and Eastern U.S. by the Northern Institute of Applied Climate Science.

Day 1 of the workshop included synthesis of science on climate and vegetation in the study area. Participants were encouraged to actively listen and use worksheets to record key insights relating to drivers, stressors, and dominant species, and potential climate impacts and adaptive capacities. These worksheets served as a reference for making vulnerability determinations on Day 2.

Day 2 involved a combination of individual and group work. For each PVT, facilitators elicited input from participants in order to fill out a master version of the notes worksheet (steps 1-4 in Figure 2), focusing on current and desired conditions of key characteristics such as species areal extent and aspects of forest structure. Participants were then asked to individually complete vulnerability worksheets, including assessments of both overall PVT vulnerability and confidence in those ratings. Each participant then recorded his/her ratings on a group, poster-sized version of the vulnerability worksheet (steps 5-6, Figure 2). We then discussed these ratings and looked for meaningful divergence and consensus (step 7, Figure 2). This process was repeated for each PVT.

Documenting these steps in the vulnerability assessment process was important for justifying the management implications and potential responses to be identified in Workshop Two. This is consistent with the notion that "…for climate adaptation to be effective, it must be carried out in a purposeful and deliberate manner that explicitly considers the effects (or potential effects) of climate change on the resources of interest, and that conservation actions should be clearly linked to these impacts" (Stein et al. 2014: 24).

The goal of the second workshop was to identity and evaluate adaptation options for vulnerable PVTs. We did this using a framework under development as a follow-up to NRAP by the USFS Office of Sustainability and Climate (OSC) (Figure 4). The approach is being designed to assist natural resource program managers and specialists with integration of climate change information in strategic program planning prior to integration into forest plan revision and project development.

The framework consists of six steps that include climate change vulnerability assessment and adaptation, culminating in integration into operations and monitoring. These steps are designed to assist forests and grasslands in identifying climate-related vulnerabilities (step 1); geographically locate, quantify (where appropriate), and/or describe site situations of varying risk related to climate-related vulnerabilities and develop a program strategy of action given the relative risk and available adaption strategies (steps 2-3); incorporate the vulnerability assessment and program strategy planning and project development (step 4); and develop methods to monitor progress, evaluate the success of these actions, and communicate learning (step 5-6). We did four exercises under step 1-3. These focused on spatially explicit consideration of stressors, adaptive capacity, vulnerability, and management priority, as well as an expert-based assessment of uncertainty in vulnerability. Rather than report the results for each of the four exercises, we integrate them into tables on vulnerability and adaptation options.

The final exercise dealt with adaptation strategies. We used the format from NRAP that specified for each of the vulnerable cover types within PVTs overarching adaptation strategy and goal, specific tactics, feasibility, effectiveness, ecological soundness, and adaptive management framework.

Table 1. Participants in the project.

Name	Affiliation	Email address
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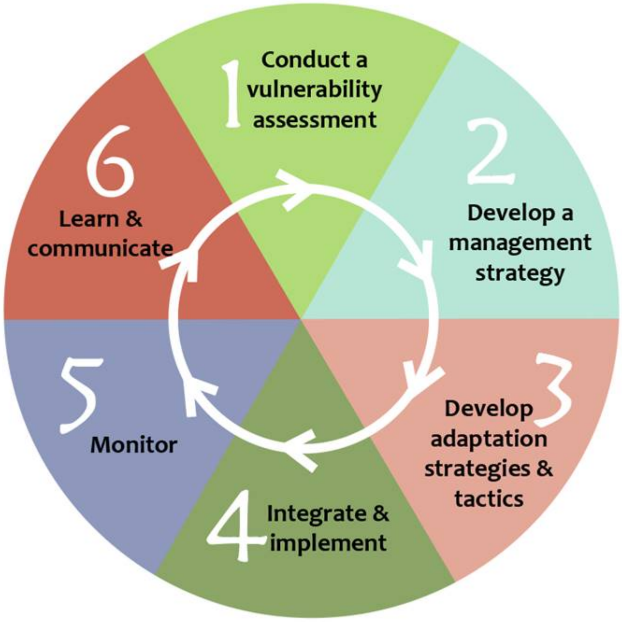


Figure 4. Framework for identifying and evaluating climate adaptation strategies. From USFS OSC (in prep.)

RESULTS

Synthesis of Current Knowledge

Climate Change and Disturbance. Climate projections indicate average temperature and precipitation will both likely increase across the GYE (Gross et al. 2016) (Figure 5A). However, increases in precipitation will not be sufficient to offset increases in drying caused by warming (Figure 5B). On an annual basis snow water equivalent and soil moisture will decline, while deficit will increase over time (Melton et al. 2016). The changing seasonality will affect vegetation primarily by initiating earlier start of growing season and imposing late season moisture deficits at lower elevations and lengthening growing seasons at higher elevations. An important consequence of warm temperatures in the future results from increased evapotranspiration causing “hotter drought” that increases relative seasonal water deficit regardless of precipitation amount.

Warming and drying climate is projected to lead to increased pest outbreaks and fire. The interaction between mountain pine beetle (*Dendroctonus ponderosae*) and climate change has already had a profound effect on whitebark pine in the GYE. Between 2004 and 2009 approximately 80% of large size class whitebark pine were killed by an epidemic of mountain pine beetle (Shanahan et al. 2016). The impacts were due primarily to temperature release on beetle development and weak defense mechanisms of whitebark pine, which did not co-evolve with mountain pine beetle (Raffa et al., 2012). Shanahan et al. (2016) found a weak positive relationship between drought stress and mortality in trees attacked by pine beetle even though drought stress was not severe during the epidemic. The beetle epidemic subsided after 2009 when October temperatures may have killed beetles before they became cold hardened. Alternatively, the reduction in large tree size classes (the preferred host for pine beetle) may have been diminished during the epidemic to low levels that effectively controlled beetle numbers

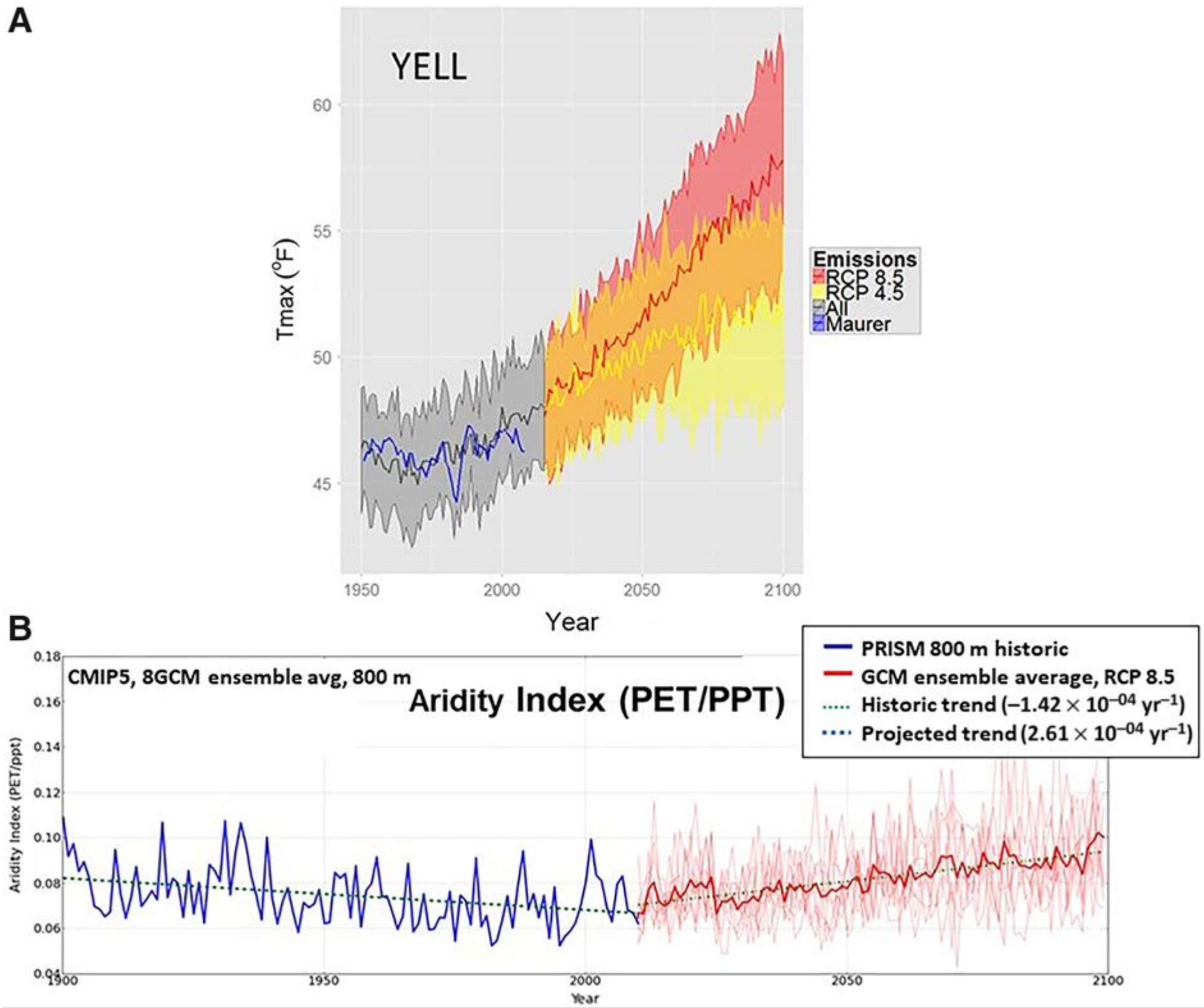


Figure 5. A) Projected average annual temperatures for the Yellowstone PACE for a higher-emissions pathway (RCP 8.5) and a lower-emissions pathway (RCP 4.5) for an ensemble of global climate models. Shaded zones are standard deviation. "Maurer" in the key represents historical data. Data are from Gross et al. (2016). (B) Historic and projected change in aridity estimated as potential evapotranspiration/precipitation under RCP 8.5. Data are from Chang (2015). RCP, representative concentration pathway. From Hansen and Phillips 2018.

after 2009. As noted above, rising temperatures will increase drought stress over time, which will also create conditions that are unlikely to impose historical thermal limits on beetle development (Bentz et al. 2003, Buotte et al. 2016).

Fire severity, frequency, and size that characterize fire regimes in the region are dependent on vegetation type and climate. The Cold PVT occupies higher elevations in the region with a boreal, cool summer climate. The high-severity fire regime is characterized by infrequent (fire return intervals of 150-300 years) stand-replacing fires since the last glacial maximum (Romme & Despain 1989, Higuera et al. 2010). Large fires, that burn more than 1000 hectares, account for the vast majority of area burned in the Cold PVT (Schoennagel et al. 2004, Balling et al.

1992). The Cool Moist PVT occupies the mid-elevations in the region with a boreal, warm summer climate and a mixed-severity fire regime, with both infrequent high-severity fires and low-severity understory fires (Schoennagel et al. 2004). Fire behavior here is driven by both fuels and climate, varying with elevation (Littell 2002, Schoennagel et al. 2004). The Warm Dry PVT occupies lower elevations in the driest climate in the region. The low-severity fire regime has frequent (fire return intervals of 20-35 years) understory fires (Littell 2002), limited primarily by fuel abundance and continuity. Fire was largely excluded from lower elevation forests in GYE during 1880-1988 (Littell 2002). Livestock grazing and human fire exclusion may have reduced fuels and fire spread during this period. Since 1988, fire area and severity have increased in the lower elevation forests, possibly associated with climate-induced drying and increased fuel loads (Figure 6).

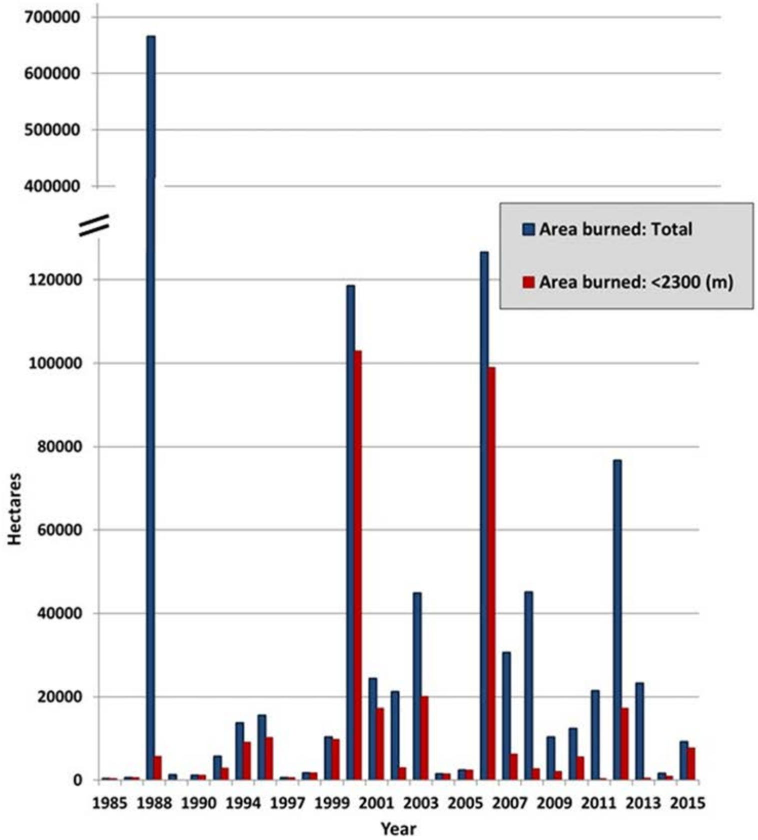


Figure 6. Area burned in the GYE totaled for all elevations and for lower elevation forests during the period of record for the Monitoring Trends in Burn Severity data set. From Hansen and Phillips 2018.

In the recent fire record starting in 1940, five of the largest fire years, based on total acres burned, have occurred since 1988 within the CGNF (Figure 7). Although 1988 was a large fire year (214,199 estimated acres burned) in the Custer Gallatin, it was not as outstanding of a year as experienced in Yellowstone National Park. In fact, an estimated 209,043 acres burned over the CGNF in 2012, comparable to the 1988 area burned. Other large fire years include 2000, 2002, and 2006 with 83,072, 64,170, and 134,815 estimated acres burned respectively.

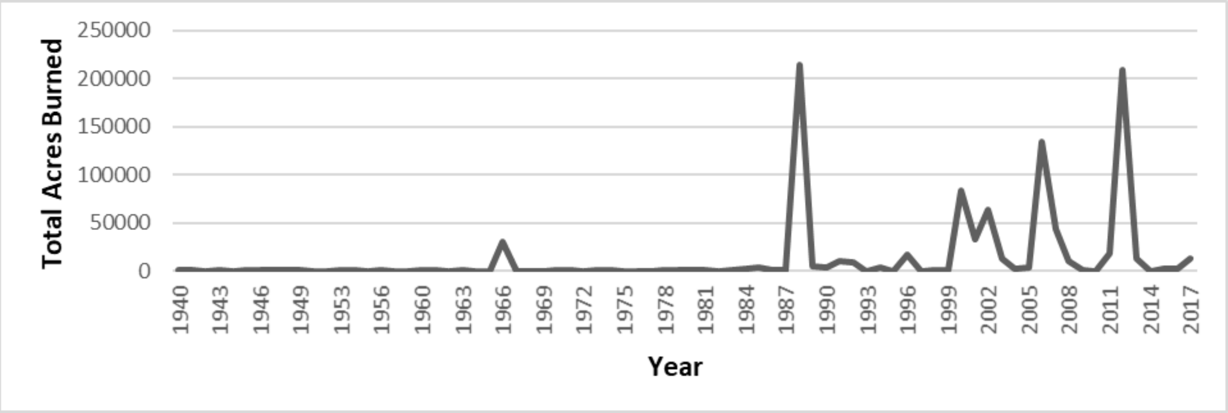


Figure 7. Total acres burned from 1940-2016 within the Custer Gallatin National Forest. Data from FAMWEB and the spatial wildfire occurrence dataset (Short 2017). From K. Emmett, unpublished report.

Projections for fire activity under future climate scenarios were done with statistical and mechanistic models. A statistical modeling approach considered climate variables only, not fuel (vegetation) characteristics, and was completed for the GYE. Westerling et al. (2011) projected changes in annual area burned and fire return intervals driven by climate scenarios from three global climate models under a medium-high emissions scenario (A2, similar to the RCP8.5 scenario). By 2075 annual area burned was predicted to exceed 1988 levels, with years with no large fires becoming rare by 2050. Their findings projected a shift in the fire return interval to <30 years by 2050 for the northern GYE encompassing parts of the Custer Gallatin, and to <10 years by the end of the century under all three global climate models.

Mechanistic models include fuel characteristics such as type, abundance, and moisture content as dynamic components that influence modeled fire behavior. Clark et al. (2017) used the mechanistic model FireBGCv2 to project future fire regimes under three future climate simulations (A2-low, A2-avg, and A2-high) for a landscape in Yellowstone National Park (YNP). Annual area burned was projected to increase between 1.2 to 4.2 times more than historical simulation values, under the coolest and warmest climate scenarios respectively. Fire return intervals were projected to decrease from the simulated historical rotation of 400 years to 336 years under the coolest climate scenario and 98 years under the warmest climate scenario, with shorter return intervals at lower elevations and longer return intervals at higher elevations. Since this study simulated the central plateau in YNP their results are most relevant to the Cold PVT.

Due to the uncertainty in future climates, the relative simplicity of statistical modeling approaches, and the compounded error from model limitations, assumptions, and uncertainties in the mechanistic modeling, the levels of uncertainty are high for future fire projections. Notably, both the statistical and mechanistic modeling referenced here assumed that the fundamental relationships between climate and fire are stationary and used relationships based on historic scenarios. Furthermore, there is higher uncertainty for fire regimes in the Warm Dry PVT specifically, since there is little research on historic and projected future fire regimes for this PVT in the region.

Vegetation response

The projected rapid changes in climate will impact the vegetation assemblages of the Northern Rockies and the GYE in both directly by shifts in growth, mortality, and regeneration, and indirectly changes in disturbance regimes and changes in other ecosystem processes, such as hydrology, snow dynamics, and exotic invasions. These responses, taken collectively, could alter the way vegetation is managed by public land agencies in this area.

The most extensive assessment of vegetation response to climate change in the Northern Rockies was done by the NRAP Halofsky et al. 2018). This project assessed projected climate change responses for 17 tree species, 5 forest vegetation types, and three resources of concern. Using the past, current, and future assessments, the NRAP assessment rated the vulnerability of the elements to climate change. Vulnerability was determined from a number of factors including stressors, exposure, sensitivity to climate change, impact of climate change, and adaptive capacity of the element. A synthesis of the vulnerability rating for the 17 tree species is presented for the entire NRAP area and for the GYE (Table 2).

Vulnerability assessment for the Northern Rockies region was also done by Hansen and Phillips (2014) based on the results of five previous studies and by Piekielek et al. (2015) for the GYE. The assessments are in general agreement that subalpine tree species are most vulnerable to climate change, particularly whitebark pine, subalpine fir, and lodgepole pine. With warming, suitable habitats for these species shift to higher elevations and have less total area. Lower elevation forests are also vulnerable with the Douglas fir zone in GYE being increasingly suitable for juniper and sagebrush (*Artemisia/ Juniperus*) communities. Forests at all elevations are projected to have increased outbreaks of forest pest species and more frequent fire. Details for individual tree species or community types in the study area are provided in Appendix I.

Considerable uncertainties underlay these projections of vegetation under future climates:

1. The complex interactions of climate with vegetation and disturbance are difficult to predict in time and space making future projections difficult;
2. There are abundant scale problems in nature and in the literature that made it difficult to generalize species and ecosystem trends at the right temporal and spatial scale;
3. The great uncertainty in climate projections (22 GCMs, 6 scenarios) made it difficult to project climate change responses at the project levels most relevant to management.

Table 2. Vulnerability of tree species (1 is most vulnerable) in the Northern Rockies and GYE. NA indicates a species is not present in the geographical area or not included in the study.

Species	**Halofsky et al. 2018**		**Hansen and Phillips 2014**	**Piekielek et al. 2015**
	Northern Rockies	**GYE**	**Northern Rockies**	**GYE**
Alpine larch	**1**	**NA**	**NA**	**NA**
Whitebark pine	**2**	**1**	**1**	**1**
Western white pine	**3**	**NA**	**NA**	**NA**
Western larch	**4**	**NA**	**8**	**NA**
Douglas-fir	**5**	**2**	**9**	**5**
Western red cedar	**6**	**NA**	**7**	**NA**
Western hemlock	**7**	**NA**	**6**	**NA**
Grand fir	**8**	**NA**	**11**	**NA**
Engelmann spruce	**9**	**4**	**5**	**2**
Subalpine fir	**10**	**5**	**4**	**3**
Lodgepole pine	**11**	**6**	**3**	**4**
Mountain hemlock	**12**	**NA**	**2**	**NA**
Cottonwood	**13**	**3**	**NA**	**NA**
Aspen	**14**	**7**	**NA**	**6**
Limber pine	**15**	**8**	**NA**	**7**
Ponderosa Pine-west	**16**	**NA**	**NA**	**NA**
Ponderosa Pine-east	**17**	**9**	**10**	**NA**
Green ash	**18**	**10**	**NA**	**NA**

VULNERABILITY ASSESSMENT

Below we summarize the background information and our conclusions about the vulnerability of cover types within PVTs to climate change. This section draws on our synthesis of current knowledge on climate and disturbance (above) and cover type summaries (Appendix I), our vulnerability assessment from Workshop One (Figure 8), and the results of Exercises 1-3 in Workshop Two (incorporated into Table 3). Details on projected change from Desired Condition under future climates are provided in Appendices II-IV.

Warm Dry PVT

The lower treeline forest in the study area is of especially high ecological and socioeconomic importance, thus its high vulnerability to climate change is an important issue for management. These forests are the most productive in the GYE (Hansen et al. 2000), they support high levels of biodiversity (Hansen et al. 2002), and they are considered highly desirable by recreationists and by exurban homeowners (based on the distribution of trails and rural homes). Stressors in the zone have been dynamic over time. Livestock grazing and fire suppression likely reduced fire in this zone since the late 1800s, allowing expansion and densification of conifers (Gallant et al. 2003, Powell and Hansen 2007). In some settings, the expanding conifer overtopped and outcompeted quaking aspen (*Populus tremuloides*), resulting in a substantial reduction of aspen (Brown et al. 2006). Since 2000, mixed and severe fire has expanded in lower tree line forests, forest pests such as Douglas fir beetle beetle (*Dendroctonus pseudotsugae*) and spruce budworm (*Choristoneura spp*) have increased, and invasive species are expanding. Consequently, conifer forests in burned areas have shifted to early seral conditions, some aspen stands are undergoing release, sagebrush and juniper communities are moving up in elevation, and old and large diameter Douglas-fir trees have been dying (observations of working group participants). This vegetation zone has been dynamic under past climates (Iglesias et al. 2018). Current trends are expected to become more pronounced under climate warming and increased fire in coming decades (Piekielek et al. 2015, Hansen et al. 2018).

We thus rated the Douglas-fir cover type in this PVT as high in vulnerability to climate change (Table 3, Figure 8). The level of confidence in this ranking was medium. More studies of Douglas fir performance in this PVT under warming and fire expansion are needed to increase confidence in the rating. In the near term, loss of the large, older cohort is of high concern. These late seral individuals provide seed sources for forest regeneration, habitat for many species of wildlife, coarse woody debris that promotes moisture retention and nutrient cycling, and have high commercial and aesthetic value to humans. In the longer term, an additional concern is loss of conifer cover and expansion of sagebrush and juniper. Conversion from forest to nonforest would have large implications for snow retention, runoff, wildlife habitat, wood production, and aesthetic values.

Both sagebrush/juniper and aspen cover types are likely to expand in this PVT in coming decades (Piekielek et al. 2015, Hansen et al. 2016). Both are of high conservation value and both have been in decline in the region in recent decades. Thus, increased warming, drought, and fire are expected to favor these cover types and reduce the need for management interventions on their behalf (such as the release from conifer competition that has been widely employed by the USFS) may no longer be needed.

Cool Moist PVT

This vegetation type has the broadest aerial distribution across the study area. The dense forest canopy across most of this type contributes heavily to snowpack retention, summer runoff, cooler stream temperatures, and habitat for forest-dependent wildlife species. The dominant tree species in this zone (lodgepole pine, Englemann Spruce, and subalpine fir) generally have high adaptive capacity to disturbance and this vegetation zone has been highly resilient to past climate, fire, and pest regimes over since the Holocene (Whitlock and Bartlein 1993, Iglesias et al. 2018). This resilience is evidenced by the rapid recovery of forests following the large fires in the GYE in 1988.

During the past decade, a bark beetle outbreak has caused high levels of mortality in lodgepole pine and especially whitebark pine. Almost the entire range of whitebark pine in the GYA was affected by mountain pine beetle during this epidemic and approximately 50% of the area showed severe mortality and 36% moderate mortality as indicated by the change in overstory condition (McFarlane et al. 2013). Mortality was especially high in drier microenvironments, which are more prominent in this PVT than in the Cold PVT. Whitebark pine has also been impacted by white pine blister rust *Cronartium ribicola*): infection rates were estimated at 14-26% at the end of 2015 (Shanahan et. al. 2017).

Projections for the coming decades indicate increases in Douglas fir in this zone (Piekielek et al. 2015, Hansen et al. 2018) associated with less frost during the growing season and warming temperatures. Lodgepole pine, subalpine fir, and Englemann Spruce are projected to decrease in biomass and age/size class due both to drying soils and more frequent fires (Piekielek et al. 2015, Clark et al 2018, Ireland et al. in prep). Whitebark pine is projected to substantially loose suitable habitat in this zone based on climate suitability modeling (Chang et al 2014). However, a mechanistic model that includes consideration of climate, fire, succession, and bark beetles projected increases in whitebark pine in this zone under the more extreme climate scenarios (Ireland et al. in prep). The long-distance dispersal ability of this species allowed it to regenerate in the extensive areas burned under that climate scenario.

There is very high uncertainty in projections of whitebark pine under future climates because the tolerances of the species to warm and dry conditions in the GYE are not known. One perspective is that the species can tolerate the warmer drier conditions at lower elevations but is limited there by competition with other conifers (Bruemeyer et al. 2016). This perspective suggests that whitebark pine will expand under climate warming and increases in fire which remove competitors. Another perspective is that whitebark pine regeneration is limited to the moister soil conditions and cooler temperatures now found at higher elevations (Chang et al. 2014). This perspective suggests that the species will contract substantially in suitable habitat under warming and drying conditions. Because whitebark pine and limber pine cannot be distinguished when cones are not present, however, and limber pine tolerates warmer and drier conditions, the regenerative tolerances of Whitebark pine have not been established through empirical study.

Thus vulnerability of this PVT is considered low to medium for all the cover types except for whitebark pine which was rated as high (Table 3, Figure 8). As stated above, evidence was considered low to medium and there was medium agreement among the group in this vulnerability ranking.

Cold PVT

Whitebark pine is the dominant species in this PVT. It is widely recognized for providing valuable ecosystem services such as pine nuts as a vital food source for wildlife, retaining snowpack and promoting summer runoff, and facilitating establishment of other tree species at treeline (GYCC 2011).

Both climate suitability models and mechanistic models project substantial reductions in area of suitable habitat and loss of larger size classes in this zone (Chang et al. 2014, Ireland et al. in prep). In association with warming temperatures, bark beetle outbreaks are projected to increase in future decades (Buotte et al. 2016). Pine blister rust is also expected to inflict increased mortality on whitebark pine under a warming climate (Keane et al. 2017). Thus, we ranked whitebark pine high in vulnerability in this zone with low to medium evidence and high agreement (Table 3, Figure 8).

Lodgepole pine, Englemann spruce, and subalpine fir are projected in have increased climate suitability in this zone and may expand in distribution and density, especially for smaller size classes (Piekielek et al. 2015). More frequent fires may reduce densities of larger size classes of these species.

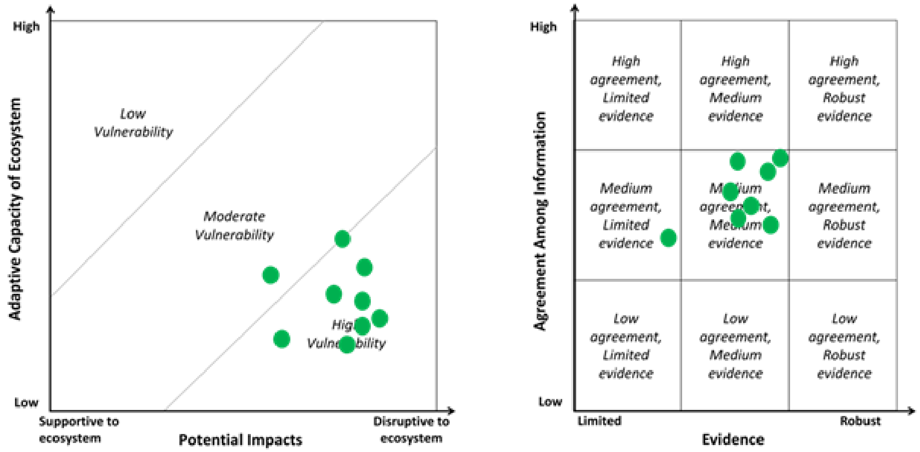
Table 3. Assessment of vulnerability of cover types within potential vegetation types.

PVT	Cover Type	Vulnerability			Projected change over 50 years	Vulner-ability ranking	Confi-dence
		Stressor/ Driver	Sensitivity	Adaptive capacity			
Warm Dry	Sagebrush Juniper	Land development, Increased fire Invasive species, especially as linked to livestock grazing and recreation	Low to moderate	Relatively drought tolerant, Tolerates low severity fire, Good dispersal ability	Increase, replacing Douglas fir at current lower treeline	Low	Low to Medium
	Douglas fir	Increased temperature, PET, soil moisture deficit Less low-severity fire, More high-severity fire, Increased disease/pests, Land development, Historic timber management	High, especially for larger size classes, Relatively seed dispersal limited	Productive soils favor high growth and resilience, Relatively fire and drought adapted	Towards densification of smaller size classes in next decade and loss at lower treeline in later decades, Reduction in large size classes	High	Medium agreement Medium evidence
	Aspen	Reduced fire, Competition from conifers, Potential reduced ground water	High, Aspen cover has been reduced over past decades due to lack of fire and conifer expansion, Potential for eventual loss of aspen if localized ground water is reduced by drought and lack of snow pack	Well adapted to fire, Able to persist under a conifer canopy for many decades and then release following canopy removing disturbance.	Stable or expanding in association with increasing low elevation fire, Role of snowpack in providing ground water to support aspen is poorly known.	Low	Medium
Cool Moist	Douglas fir	Longer growing season,	Frost is currently	Relatively fire and drought adapted, Likely	Increase in density of younger/smaller	Low	Low to medium evidence

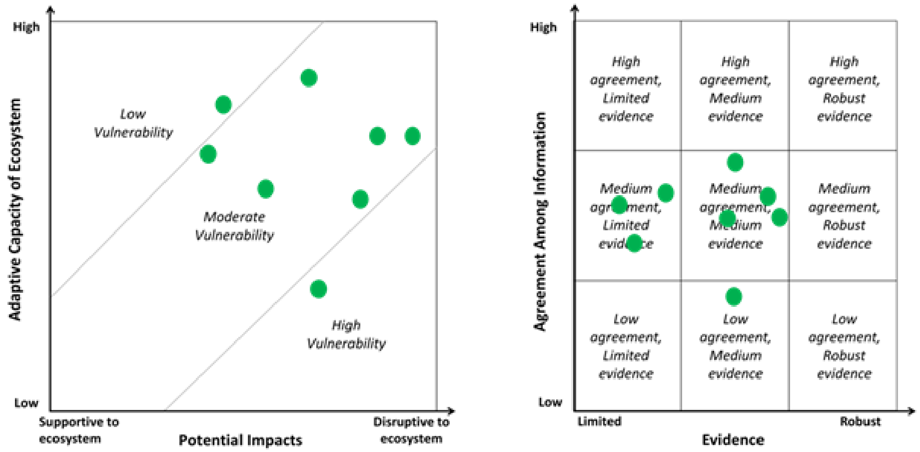
		Less frost damage, Increased fire	limiting in this zone	able to disperse to higher elevations from current distribution	size classes, possibly above desired range		and agreement
	Lodgepole pine	Warmer temperatures, Reduced snowpack, Reduced soil moisture, Reburns before trees reach reproductive age, Increased pests, Higher productivity and more rapid succession, could further increase homogeneity, Larger burned areas further fosters homogeneity	Moderate to high, All models project reduced density and age/size in this zone under future climate	Well adapted to fire, High regeneration following pest outbreaks, Fast growth rates, Good competitor	Decrease in density and age/size classes from desired range	Medium	Low to medium evidence and agreement
	Englemann Spruce/ Subalpine fir	Warmer temperatures, Reduced snowpack, Reduced soil moisture, Higher productivity and more rapid succession, could further increase homogeneity, Larger burned areas further fosters homogeneity	Do not tolerate dry soils, Not well adapted to fire,	Good competitors, Moderate seed dispersal, Persisted well through widely variable conditions over past millennia	Decrease in density and age/size classes from desired range	Low to Medium	Medium evidence, Low agreement
	Whitebark pine	Warmer temperatures, Reduced snowpack, Reduced soil moisture, Increased competition from Douglas fir, Increased disease/pests	Poor competitor, Poorly adapted to disease and pests, Slow growth, long generation time	Good disperser, Regenerates well following disturbance	Decrease in density and age/size classes from desired range	High	Low to medium evidence, Medium agreement
Cold	Lodgepole pine	Warming, Increased winter minimum temperature,	Projected to expand upslope under warming,	Well adapted to fire and increased warming	Increase in density of smaller size class	Low	Low to medium evidence

		Reduced snowpack, Reduced frost kill, Soil moisture deficit, increased competition, Increased disease and pests	drying, and increased fire				and agreement
	Englemann spruce/ Subalpine fir		Projected to expand upslope with longer growing seasons, Sensitive to increased fire	Relatively rapid growth rates under favorable conditions allows successful competition		Low	
	Whitebark pine		Poor competitor, Poorly adapted to disease and pests, Slow growth, long generation time	Good disperser, Regenerates well following disturbance	Decrease in density and age/size classes from desired range	High	Low to medium evidence, High agreement

Potential Vegetation Type: Warm Dry



Potential Vegetation Type: Cool Moist



Potential Vegetation Type: Cold

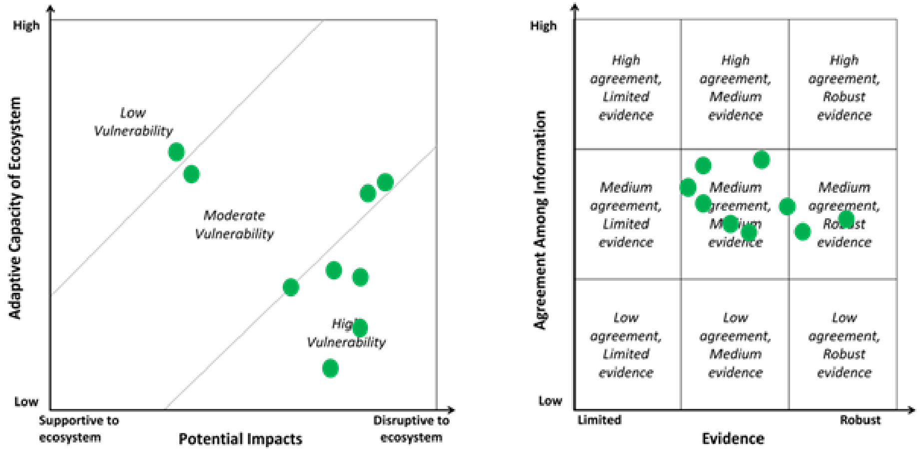


Figure 8. Ranking of vulnerability and level of confidence using the method of Brandt et al. (2017). Each dot represents the vote of a member of the working group.

ADAPTATION STRATEGIES

The primary outputs from this project are recommendations for the forest plan revision of goals, strategies, tactics that can be employed to increase resilience of the forest ecosystem to climate change. For vulnerable cover types within PVTs, adaptation goals and strategies were specified based on a synthesis of the literature and expert knowledge and opinion of the working group. Further, we evaluated feasibility of the tactics, likely effectiveness, ecological soundness, and mention how these can best be done in the context of adaptive management.

Strategy 1: **Prevent conversion of Douglas-fir to grassland in the Warm Dry PVT**. This strategy is aimed at reducing loss of Douglas-fir forests and expansion of sagebrush/grassland community types at lower treeline under warming and drying climate. The overarching goal is to create or maintain characteristics that help the Douglas fir cover type be resistant and resilient in the face of climate change and the projected increase in fire and pests. The tactics included mechanical thinning and patch timber harvest, uncontrolled fire (natural) and controlled fire (prescribed), and controlled recreational access (Table 4). The objectives for these tactics are to reduce fuel loads and fuel contiguity to lessen the likelihood of severe fire (Larson and Churchill 2012), increase spacing among trees to increase growth rates and vigor of individual trees, and reduce human fire ignitions. All of these tactics have been vetted by the USFS in the past but their effectiveness and feasibility are relatively well known. Mechanical thinning and patch timber harvest are likely to be most effective, but have substantial ecological and social constraints, and thus are low in feasibility. Controlled and uncontrolled natural fire are more difficult to manage and thus are low or medium in likely effectiveness but are medium to high in ecological soundness. Permitted firewood cutting and control of recreational access are both considered low in effectiveness.

While none of the tactics stands out as high in both likely effectiveness and potential feasibility, this adaptation strategy can likely be achieved by distributing all the tactics prudently across the landscape to maximize benefits and minimize constraints and risks. For example, use of controlled and uncontrolled fire may be preferred in locations without human dwellings. Mechanical treatments may be required in such settings and make more feasible by the road infrastructure associated with homes and USFS access.

Table 4. Tactics and evaluation of adaptation strategy to prevent conversion of Douglas-fir forest to non-forest types at lower treeline.

Tactic	Mechanical thinning	Controlled fire	Uncontrolled fire	Patch timber harvest	Control recreation access
Objective	Reduce stand-replacing fire by reducing fuel loads; reduce stand density to favor larger and more resilient fire-adapted trees	Lower fuel loads with fire during times when severe fire is not likely; maintain fire-adapted species	Reduce fuel loads by allowing natural fire during lower-severity burn conditions	Increase age-class heterogeneity within stands to reduce contagion of high-fuel loading across landscape	Reduce chance of accidental fires
Likely effective-ness	High. Fuel loads and stand density can be tightly controlled	Medium. Heterogeneity in fuels reduction is likely; difficult to achieve Rx targets	Low. Difficult to control fire severity and fuels reduction vs loss of desired live trees; too near dwellings	Medium. enhances control of fire spread except during dry, windy conditions	Low. Human ignitions from recreationists is relatively uncommon
Ecological Soundness	Low. Impacts from logging; slash problems; road issues	Medium-High. Somewhat mimics native fire regimes	High. Most closely mimics native fire regimes	Low-Medium. May create structures that have not occurred in the past; problems with slash	High. Less chance of human influence
Potential Feasibility	Low. Social and ecological constraints on roading, visuals, loss of wildness	Medium. Social constraints due to risk to humans/property, and smoke effects	Medium. Social constraints due to risk to humans/property, and smoke effects	Low. Social and ecological constraints on roading, visuals, loss of wildness	Low. High public demand for recreational access
Integration of tactics across landscape	Distribute tactics across the landscape based on vulnerability of lower tree-line forest, road access, risk to lives/property, wilderness character, visuals, social acceptance, try to mimic patch structure of historical landscape patterns				

Strategy 2: **Maintain large diameter Douglas-fir in a savannah setting in the Warm Dry PVT**. The goal of this adaptation strategy is to maintain large Douglas-fir trees in lower tree-line settings and sustain the ecosystem services they provide. The tactics involve managing to reduce the occurrence of severe fire, enhancing growth rates of medium diameter stands to recruit large trees, and reducing insect and disease impacts (Table 5). The means of executing these tactics are similar to those discussed under the first adaptation strategy (e.g. fire facilitation/exclusion, mechanical thinning, control of insects/disease). Thus, likely effectiveness and feasibility are similar to those discussed above. Ongoing monitoring and evaluation will be needed to gauge effectiveness. Burn severity should be better monitored to evaluate treatment effectiveness and forest response. Stand structure and composition should be monitored at scales finer than is currently being done by the Forest Inventory and Monitoring program. High resolution imagery such as Google Earth could be used for project and stand scale monitoring.

Table 5. Tactics and evaluation of the adaptation strategy to maintain large-diameter Douglas Fir in a savannah setting at lower treeline.

Tactic	Manage fire by mapping fire risk, managing fuels, and fire exclusion practices	Understory thinning, fuels management, severe fire exclusion practices to favor growth	Mechanical treatment and use of low severity fire to manage landscape pattern.	Use of pesticides to control pests, thinning to increase vigor and stand heterogeneity
Objective and Rationale	Maintain existing stands of large-diameter Douglas Fir in a savannah setting by avoiding severe wildfire. While these stands are dependent upon low-severity fire, high-severity fire weaken and kill large diameter Douglas fir trees.	Facilitate growth of medium diameter stands into large diameter stands. Tree growth rates are relatively rapid in lower treeline and opportunities exist to manage for sustainable production of large diameter trees from smaller ones.	Create heterogeneity of size classes across the landscape. Variation in age class and forest structure across the landscape reduces spread of severe fire, insects and disease.	Protect large trees from insect and disease infestations. Insects and disease are currently important causes of mortality and this is likely to be increased by climate change.
Likely effectiveness	High. Stands with large trees are generally savanna like and amenable to effective management	High, but decades are required. A sustained effort would be required over decades to grow larger trees.	High. The paleo record shows that heterogeneous lower-treeline forests were sustained for many centuries in presettlement times (Littell 2002)	Medium to low. Treatments to inhibit Douglas fir pests and diseases are not well developed and are rarely effective except at high costs
Ecological Soundness	High. Mimics NRV fire regimes	Low-Medium. Impacts from logging; slash problems; road issues		

Potential Feasibility	Moderate. These areas are often close to roads, not in wilderness or other restricted mgt classes; challenges include smoke, risk of burning homes/property in the wildland urban interface, visual issues with mechanical thinning, exotics can exploit openings	Moderate to low. Managing forest pests at scales large enough to large trees across the landscape is challenging.
Integration of tactics across landscape	Ensure that the stand-level treatments are put into the landscape heterogeneity context	

Strategy 3: **Implement the GYCC Whitebark pine strategy in the context of climate change**. The GYCC Whitebark Pine Subcommittee has developed a rigorous and fully vetted strategy for managing this species in the GYE (GYCC 2011). This adaptation strategy is aimed at implementing that plan in the context of climate change. The tactics advocated in Table 6 are identical to those in the 2011 strategy, except that we advocate placing this tactics in the landscape with consideration of climate refugia (areas less likely to change from present) and future whitebark pine habitat suitability as developed in Hansen et al. (2016) and mapped in Ireland et al. (2018). Current mapping of macro refugia by the USFS integrates consideration of climate and whitebark pine genetic diversity, colder tolerance, and rust resistance (Mahalovich et al. 2018). This approach shows high promise for guiding placement of treatments on the landscape. It is particularly important that all of the tactics be applied across biophysical gradients. The results will reduce knowledge uncertainty and allow management to be increasing tailored to local environmental conditions. Unfortunately, both the feasibility and effectiveness of maintaining large live reproductive Whitebark pine trees across the study area under climate change are low. Despite rigorous management attempts, large size classes of this species and the ecosystem services they provide are likely to be greatly diminished under future climates. Employing the recommended tactics, however, may allow adequate reproduction of medium sized individuals to perpetuate the population. Thus, it is critically important that this adaptation strategy be fully implemented.

Table 6. Tactics and evaluation of the adaptation strategy to implement the GYCC Whitebark pine strategy in the context of climate change.

Tactic	Use of controlled fire or mechanical thinning, especially in climate refugia	Use of insecticides and pheromone treatments as feasible, use of controlled fire	Plant rust resistant seedlings	Practice adaptive management
Objective and Rationale	Maintain reproductive individuals , especially in climate refugia through protection from severe fire and reduced competition This age class has undergone the highest mortality, yet is most vital to reproduction. Thus it is essential to population viability.	Control mountain pine beetle outbreaks in climate refugia and create heterogeneous age classes across the landscape. Beetles are the proximate cause of mortality and are synergistic with climate warming. Treatments to reduce outbreaks are important to increase tree survival rates,	Establish rust-resistant seedlings, especially in areas projected to remain suitable habitat under future. Blister rust is increasing in prevalence across the GYE and is expected to become a major source of mortality. Planting rust-resistant	Monitor whitebark pine establishment, growth, reproduction, and survival across biophysical gradients and in treated areas to increase knowledge of the fundamental niche and treatment response to refine management approaches accordingly. Adaptive management monitoring experiments are needed to increase our level of certainty about whitebark pine climate tolerances and

	The best hope of success is in areas projected to change least in climate. These trees provide potential avenues of enhancing rust-resistance	especially to increase potential of enhancing rust-resistance.	seedlings can ensure a portion of the population can cope with blister rust.	effectiveness of treatments across environmental gradients
Likely effectiveness	Medium. Mechanical thinning has been shown to be highly effective depending on local site conditions. Fire management will likely become increasingly challenging under future climate conditions	Low-Medium. Insecticides will likely be relatively ineffective due to inadequate scale of treatment. Maintaining diverse age classes across the landscape can be effective in reducing pest outbreaks.	High. Establishing stands through planting has been effective to date. Expansion of the rust resistant population should increase survival from blister rust infections.	High. Increased knowledge of species tolerances will allow more effective management; there are ample sampling procedures and software packages to support this effort
Ecological Soundness	Low-High. Controlled fire may mimic NRV fire, mechanical thinning has logging, slash, road impacts	High. No known ecological impacts	Medium-High. Hand planting has few ecological impacts	High. Monitoring can be done with few impacts
Potential Feasibility	Low. In portions of the forest where active management is limited (e.g., designated wilderness), fire management, especially WFU, is likely the most feasible tool. However increased fire severity and frequency, increased pest outbreaks, and logistical inhibitions on treating insects at landscape scales render these tactics low feasibility. Both of these tactics are cost-prohibitive		High. Thus far, this approach has been highly feasible.	Medium-High. The NPS I&M monitoring program has demonstrated high success and their methods could be expanded to meet this challenge but adequate funding is required
Integration of tactics across landscape	Strategically place treatments within core, deteriorating, and newly suitable climate habitats (see Ireland et al. 2018) to best achieve objectives; maintaining heterogeneous landscapes important (must include all other pine forests);			

DISCUSSION

Relevance of the Results to the Forest Plan Revision

USFS Forest plans are required by the National Forest Management Act of 1976 and are comprehensive documents that guide forest management for >=15 years. Plans specify what, where, and how the USFS manages a national forests. While forest plans do not authorize site-specific activities or prohibitions, all subsequent proposals and projects must comply with the approved forest plan. The steps in revising a forest plan are depicted in Figure 9. Our project began when the draft proposed plan was out for public comment and was completed prior to the writing of the draft environmental impact statement. Thus, this report can be used to inform the EIS, the final forest plan, and the design of implementation strategies and the follow-up monitoring and evaluation.

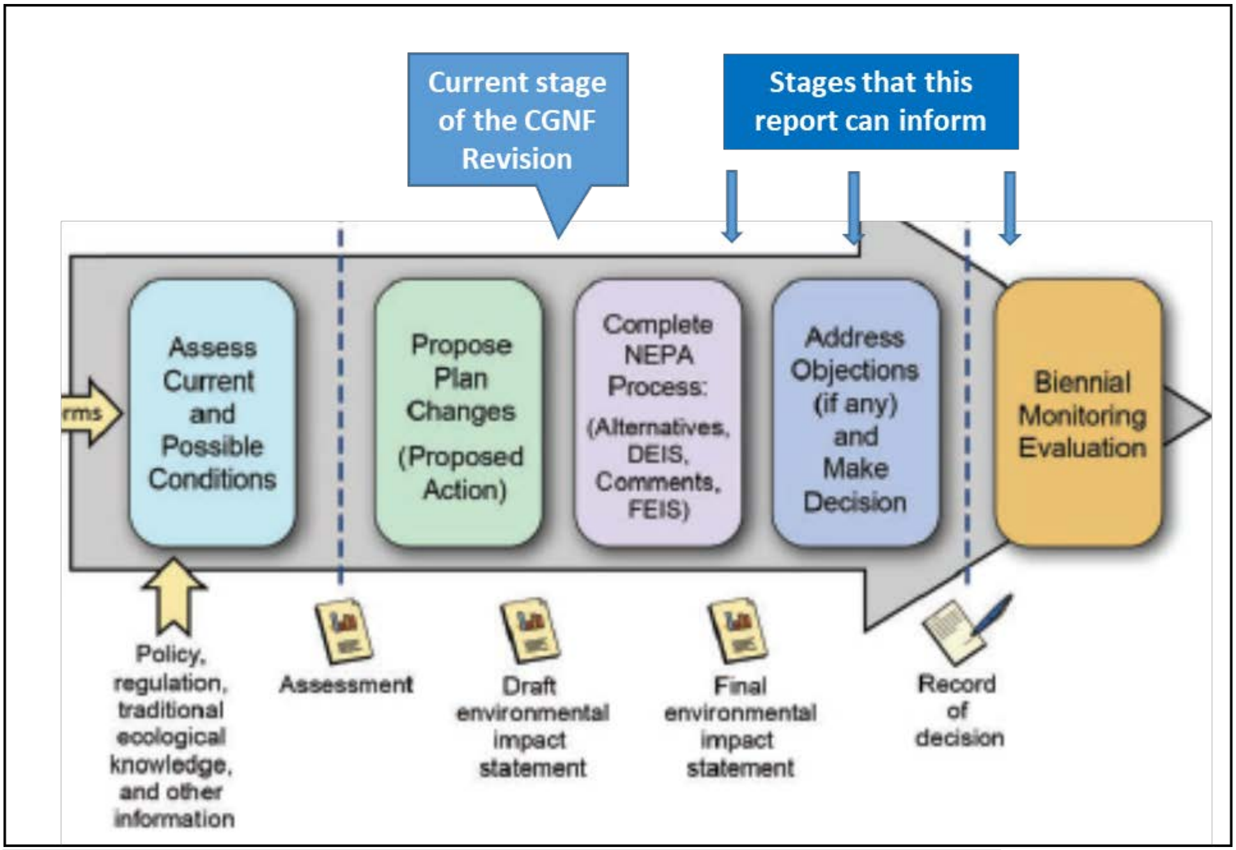


Figure 9. Steps in the USFS Forest Plan revision process.

National forests are required to develop plans that ensure ecological integrity (as defined in the Introduction) in meeting sustainability and diversity requirements. To meet the goal of ecological integrity forests specify:

- Desired Conditions – These are descriptions of specific social, economic, or ecological characteristics of the plan area, or a portion of the plan area, toward which management of the land and resources should be directed. The CGNF has defined NRV of structure, function, and composition of cover types and PVTs as the Desired Condition for the forested vegetation.

- Objectives – These are conscious, measurable, and time-specific statements of a desired rate of progress toward a desired condition or conditions, based on reasonably foreseeable budgets.
- Standards – These are mandatory constraints on project and activity decision-making, established to help achieve or maintain the desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.
- Guidelines – These are mandatory constraints on project and activity decision-making that provide flexibility for different situations so long as the purpose of the guideline is met.
- Goals – These are broad statements of intent, other than desired conditions, that are usually related to process or interactions with the public.
- Suitability of Lands – These plan components identify areas of land as suitable or not suitable for specific uses (such as timber or range production), based on the applicable desired conditions.
- Management Approaches - Describe the principal strategies and program priorities to carry out projects and activities developed under the plan can convey a sense of priority and focus among objectives and the likely management emphasis; may discuss potential processes such as analysis, assessment, inventory, project planning, or monitoring. Use care not to create unrealistic expectations regarding the delivery of programs.

This report was written to provide information useful to the formulation of each of these components of the revised plan and help guide management actions and monitoring over the lifespan of the plan.

The forest currently emphasizes using NRV to set Desired Condition to meet the goal of maintaining ecological integrity. This approach has been widely embraced for ecosystems where current conditions do not substantially differ from NRV and managing towards NRV is likely to increase resilience of the ecosystem under future change (Keane et al. 2009). Some ecosystems are so modified by humans that the NRV approach is not logically defensible and managing based on setting explicit ecological objectives is advocated (Hobbs et al. 2010). Our review and discussions of the NRV concept and its application by the CGNF led us to conclude that managing towards NRV is a reasonable approach for the CGNF given the current relatively natural state of the forest ecosystem and projected future change. How to maintain some cover types within NRV in the face of changes in climate and disturbance will likely represent a substantial challenge, however.

Considerations and Suggestions

Our synthesis of current knowledge on recent and projected climate, disturbance, and vegetation dynamics revealed that maintaining ecological integrity on the CGNF will be increasingly challenging. The pace of forest change is likely to accelerate and levels of certainty in projecting these changes are low. The CGNF can likely best meet its forest resource objectives by attempting to anticipate change, planning and managing to maintain ecological resilience in the face of this change, and embracing adaptive management methods to evaluate and improve success. The forest planning process is well designed for the forward-thinking, proactive approach most likely to be most successful under climate change. This report is intended to help inform the CGNF plan revision by identifying most vulnerable vegetation cover types within PVTs and identifying and evaluating adaptation strategies that can be incorporated into the revised forest plan. To this end, our discussions revealed several considerations and suggestions that maybe helpful in managing the forest under future change.

- Successful management of vegetation and ecosystems during this period of rapid environmental change will require “anticipatory” planning and management. Trends in climate, land use, invasives, recreation, etc., should be tracked past to present and projected into the future to allow current management strategies to be designed to help the ecosystem be resilient to the changes that may be happening in future decades. Plotting natural range of variation from past periods, trends in condition in recent decades, and projected trends provides a context for vulnerability assessment and prioritizing management needs.
- Given uncertainty in some tree species tolerances to climate and soils and high uncertainty in future climate and vegetation response, adaptive management and experiments across biophysical gradients are needed for reducing uncertainty.
- Well-designed monitoring of climate, vegetation, and ecological conditions is important for tracking the condition of key response variables in the context of management and environmental change. Many vital signs of ecological integrity can now be quantified at relatively low cost from remote sensing and other data sources (See YNP 2017, Hansen and Phillips 2018). The federal agencies present in the GYE are all doing some level of monitoring and coordination among them is most likely to lead to robust monitoring across the ecosystem.
- While there is high uncertainty in projections of future climate and vegetation response (Belote et al. 2018), there is high agreement that some trends are likely and these should be considered by management. These include increased in fire, reduced soil moisture at lower elevations, warming effects at upper treeline, reduction in snowpack and river flows, and increased levels of disease and pests.
- The spatial and temporal patterns with which these trends are manifest may be gradual or episodic due to interactions between natural climate variation, human effects on climate, and random events. For example, the shifting upslope of lower treeline under warming may be gradual with drought induced tree mortality or episodic with a large, intense fire causing a regime shift to the community. Management strategies should be robust to these varying types of change.
- Many of the tree species may be relatively resilient to projected climate with regards to regeneration and distribution. However, increased fire is likely to shift current forests to younger age classes and smaller size classes. This would reduce the habitat qualities and ecosystem services associated with large trees and late seral forests. As such, maintaining and increasing large tree structure across the landscape should be a priority.
- The Cold Potential Vegetation Type (PVT) spans a relatively wide range of climate conditions from dry to wet. Thus, vulnerability may vary across the PVT and more landscape specific management approaches may be appropriate. Ireland et al. (2018) provide an approach for tailoring management to specific landscape settings.
- District rangers and other management decision makers will benefit from information that equips them to do anticipatory management. The CGNF should endeavor to develop and effectively communicate such information. The CGNF should be making decisions about

projects based on a good understanding of past ecological drivers and responses and anticipated futures, and which management actions can be effective in those conditions.

- While the USFS has capacity limitations in how many acres can be "treated" in a given year to reach management goals, decision about management of wildland and prescribed fire can influence large acreages' and should be more fully embraced as a management tool.

Scope and Limitations

This project was carried out with a limited budget and a relatively short time frame (ca 6 months). While the project benefited from several previous climate adaptation workshops and projects, we also faced synthesizing vast amounts of new information and developing common language and values among the participants. Our self-critique of the project is summarized as follows.

Strengths

- Participants represented diverse disciplines and perspectives including forest line officers, forest planers, ecologists, wildlife biologists, fire management specialist, climate scientists, hydrologists, and experts in climate adaptation planning.
- Current knowledge was synthesized including studies using several methodological approaches and having differing conclusions.
- Conclusions on vulnerability assessment and management strategies were drawn through team consensus after extensive discussion.

Weaknesses

- Due to schedule conflicts, not all team members were able to participate in all of the project activities.
- More time would have been desirable for completing the various exercises. The one day dedicated to the vulnerability assessment and 1.5 days to the adaptation planning could have been productively doubled given the scope of the tasks.

Opportunities for Communication

Effective communication of the key findings of this report is essential to ensure follow-through from land managers and understanding by the general public. The authors recognize that the delivery of the essence of the report needs to be tailored for each audience to keep the content accessible and relevant. To meet this objective we recommend the involvement of a science communication specialist. With that caveat, we provide a few insights into how we think the report may be best communicated.

For forest managers, we recommend providing a presentation during a scheduled team leadership meeting. The presentation and discussion (~1 hour combined) would be led by one of the agencies' own employees. A separate scheduled meeting for the forest plan revision team and resource management specialists, including vegetation and fire managers, would involve a more in depth presentation on the relevant topic followed by a group discussion. In addition to the full report, an executive summary (2 pages) would be available. The content of the presentations would focus on the key findings and how these are incorporated into the forest plan revisions while providing a brief overview of the process of the development of the report. The presenter would also briefly acknowledge outstanding needs for research, future directions, and funding options for moving forward with climate adaptation planning.

For communication to the public, we reemphasis the need for a science communication specialist to aid in making the report content more accessible and germane to the general public. Ideally, the communication specialist would help create talking points and a press release of the report findings. The lead author of this report, Dr. Andrew Hansen, is scheduled to present the report results during a Forest Plan workshop to be held the day after the 14th Biennial Scientific Conference on the Greater Yellowstone Ecosystem in September of 2018. This presentation will be video recorded and made publically available. Further outreach endeavors are to be determined.

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APPENDIX I. TREE SPECIES AND PLANT COMMUNITY RESPONSE TO CLIMATE CHANGE.

Whitebark pine -Kristin Legg

Current Range in the GYA. Whitebark pine (*Pinus albicaulis*) is found on approximately10% or 2.5 million acres of the 24-million-acre Greater Yellowstone Area (GYA). It typically occurs above 8,500 feet typically in pure stands on harsh, high-elevation sites and in mixed conifer stands below the treeline. Whitebark mostly occurs on public lands usually on designated or recommended wilderness. The 2011 Whitebark Pine Strategy (GYCCWPSC 2011) for the GYA is an interagency collaboration to maintain functioning WBP ecosystems through research, monitoring (status and trend; management effectiveness), protection, and restoration.

Threats and Current Status. The prominent threats to whitebark pine are non-native pathogen white pine blister rust (*Cronartium ribicola),* mountain pine beetle (*Dendroctonus ponderosae*),wildland fire (past fire management practices reduced fire in whitebark pine habitat leading to competition with other species and increased fire intensity due to fuel loads resulting in loss of whitebark pine when fires occur), and climate change (warming temperatures and shifts in precipitations patterns). Whitebark pine is impacted by these factors differently across its range, for example the northwest Montana whitebark pines were significantly affected by blister rust whereas in the GYA the recent mountain pine beetle epidemic has had a greater impact. In the southern Sierra Nevada region whitebark have been limitedly affected by either of these factors to date.

In the GYA white pine blister rust infection rates are estimated at 14-26% at the end of 2015 (Shanahan et. al. 2017). The interagency long-term monitoring program (GYWBPWG 2011) is further examining monitoring data to better understand how long it takes blister rust to transition from branch infections to bole infections which are considered more lethal. By 2015, it is estimated that 26% of trees greater than 1.4 meters tall have died since this ground-based monitoring began in 2004 with a majority of the trees in the largest size classes. Studies of whitebark pine using remote sensing and aerial overflight techniques estimated that almost the entire range of whitebark pine in the GYA were affected by mountain pine beetle during the epidemic and approximately 50% of the area showed severe mortality and 36% moderate mortality as indicated by the change in overstory condition (McFarlane et al. 2013). This reflects a significant loss of the larger cone producing trees. As a result there is a shift to a smaller cohort of trees (based on diameter breast height [DBH] measurements) remaining on the landscape (Shanahan et al. 2016). With a shift towards smaller trees, there is increased concern for how these trees may be affected by blister rust (Shanahan et al. 2016). Wildfire has burned approximately 762,000 of the GYA from 2004 through 2017. These wildland fires have impacted about 10% of the long-term monitoring transects.

There was no evidence that during the mountain pine beetle epidemic that trees with blister rust were more likely to be attacked by beetles whereas there was some indication that trees with more soil moisture available (i.e. less droughty) were more likely to fend off mountain pine beetle attack (Shanahan et al. 2016). Additionally trees of all diameter size classes above 1.4 meters tall have been documented baring cones, although obviously the most productive trees are in the larger diameter size classes (i.e. > 10cm DBH) (Shanahan et al. 2017).

Climate research available for GYA. Prior to the 2011 GYA whitebark pine strategy there was little information available on the potential affects climate change on whitebark pine in the region. Since then there have been numerous studies as well as a US Forest Service technical report on restoring whitebark pine ecosystems in light of climate change (Keane et al. 2017). Paleo research investigated the presence of five needle pine pollen spores in lake sediments and found that five needle pines have always remained present on the landscape and limitations to site occupation were a result of winter conditions and biotic competition (Iglesias et al. 2015).

Future projections show a reduction in whitebark pine range. Climate Envelope Modeling had a decrease in suitable habitat for whitebark pine based on current whitebark pine occupancy and projected climates (Chang et al 2014). Suitable habitat for whitebark pine was at the highest and coolest elevations of the GYA (Beartooths/Wind Rivers). Keane et al (2017) also showed a reduction in suitable habitat for whitebark pine to the highest elevations; see figure and description below from Keane et al. 2017. Ireland et al. (2018) presented a model that describes the direct and indirect effects of climate projections on whitebark pine (see below).

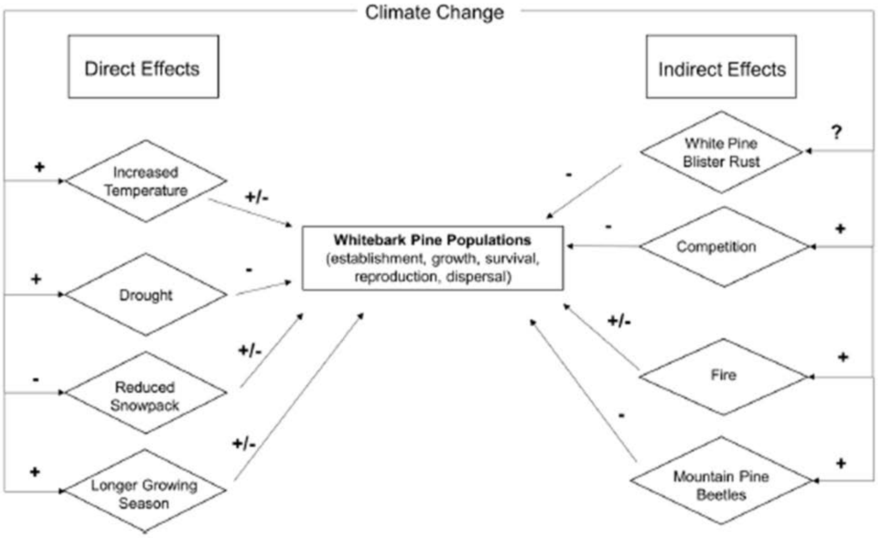

Fig. 2 Conceptual model describing the projected direct and indirect effects of future climate conditions on WBP. Positive and negative signs indicate the nature of the effect (adapted from Hansen et al. 2016)

Research has shown that climate conditions are going to become more favorable for mountain pine beetle in the future and therefore increased likelihood of epidemics or even a shift in endemic levels of beetles with more present (Buotte et al. 2016).

Genetic research is a critical piece in understanding both current whitebark pine presence as well as future survival. Whitebark in the GYA seed zone have a greater resistance to blister rust and are also more drought tolerant (Mahalovich pers. Comm).

Actions. While a decline of whitebark pine is predicted to occur under future climate scenarios, restoration actions such as planting rust resistant seedlings and employing other strategies such as protection from mountain pine beetle and thinning treatments to reduce completion and fire intensity (Keane et al. 2017). A number of efforts are underway to improve upon where to plant whitebark pine and will take into consideration both macro and micro-refugia (Mahavolich pers comm/in prep, Shanahan et al 2016). These refugia sites take into consideration climate and site characteristic (i.e. aspect, soils, slope, elevation) interactions at specific locations on the ground to improve tree survival (resilience and persistence). Matching genetic resources to sites projected to support whitebark pine in future climates would ensure species persistence and provide important wildlife food into the future (Mahavolich et al 2016).

In addition a number of research papers explored how managers can incorporate these scientific results into whitebark pine conservation. (Hansen et al 2016, Buermeyer et al 2016, Ireland et al. 2018). Specifically, modeling how effective management actions will be under future climate projections (Ireland et al. 2018) will be useful to mangers and what adaptive approaches can be taken to ensure the presence of whitebark pine into the future.

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Engelmann Spruce/Subalpine fir - Gunnar Carnwath

Historical and current distribution and spatial patterns. Subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) are widely distributed, major components of mid to high elevation forests. At mid-elevations spruce and fir are often found with Douglas-fir and lodgepole pine. Subalpine fir is usually the climax tree species in most subalpine areas of the Northern Rockies, although it sometimes shares climax status with spruce as both species are shade tolerant and fire intolerant. Pure Engelmann spruce communities are found in seasonally wet areas and riparian settings, and in severe frost pockets where all frost-sensitive tree species are excluded. In part due to fire suppression policies, spruce-fir cover types have generally increased in Northern Rockies. In particular, prevalence in understory and density has increased, particularly at the lower elevation extent of their distribution. In contrast, at higher elevations, where forests are generally characterized by more infrequent and high intensity fire, the distribution of subalpine fir and Engelmann spruce and have likely been less impacted by fire suppression. Subalpine fir has recently made gain at upper tree line as it replaces rust- and beetle-killed whitebark pine. (Halofsky et al 2018)

Future Projections. The future of subalpine fir and Englemann spruce will depend on the balance of likely expansion in the upper subalpine due to the direct effects of climate increasing suitable habitat countered by possible losses in the drier, lower extent of their distribution due to increased fire, drought and associated increases in pathogens. Climate change may allow longer growing seasons and higher productivity in subalpine communities where cold and snowpack duration limit regeneration and growth; production and regeneration are likely to increase, especially in those high mountain environments where water is rarely limiting. In particular, increase presence is expected where snow historically controlled regenerative success. Moreover, subalpine fir may increase as it replaces rust- and beetle-killed whitebark pine at the upper end of its distribution in the GYE (though whitebark pine can also facilitate subalpine fir establishment by ameliorating harsh environmental conditions). SDM models have a wide range of predictions from large losses of subalpine fir. (Hamann and Wang 2006) to minimal change in its distribution (Bell et al. 2014). Hamann and Wang (2006) projected a 27-percent decrease in the range of Engelmann spruce in British Columbia by 2050. Coops and Waring (2011) used mechanistic modeling to simulate a retraction in spruce range of more than 50 percent. Notably, Various SDM approaches project minor changes in the spruce-fir subalpine zone (Bell et al. 2014; Crimmins et al. 2011).

Seedling establishment may be the bottleneck for subalpine fir and Engelmann spruce in the future as years that meet these conditions may be less frequent in the future in the lower subalpine. Andrus et al (2018) showed that large establishment events of spruce and fir occurred in years of high soil moisture availability and suggested that maintaining subalpine forests, declines in the frequency of establishment events are likely to compound the effects of increasing mortality from fire and drought.

*Uncertainty. U*ncertainty is moderate to high for these species due to the potential for counter-acting forces at the lower and upper end of its elevational distribution

Summary Subalpine fir and spruce are rated by Halofsky et al (2018) as moderate vulnerability due to low exposure but moderate assessment in terms of magnitude and likelihood of effects. Currently stands are higher density, increasing susceptibility to disturbance. Increasing fire will dramatically reduce populations; fire exclusion may foster expansion. Increasing subalpine temperatures may increase growth and accelerate succession toward fir-dominated stands. As competition increases, the warmer climates may facilitate increased mortality from insects and disease as trees become more stressed from high densities.

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Lodgepole pine -Tom Olliff

Background. Greater Yellowstone is not at, but toward, the southern end of lodgepole pine (LP) range. North and south of us LP can inhabit a wide range of elevation and soils—in the GYA, it seems to be somewhat constrained by geology—that is, it typically does best on the rhyolitic soils created from the most recent, 600,000 year old lava flow on the YELL plateau.

Lodgepole is a fire dependent species, but it is important to distinguish between different successional stages of LP, especially in terms of size classes, large trees, snags, and course woody debris in our projected vegetation futures.

Recently burned LP—LP0—is up to 40 years old. It consists of seedlings, saplings, forbs, grasses and rotten logs. If anything burns in these forests it tends to be the rotten logs. Don Despain, Yellowstone's long-term vegetation ecologist, refers to these as "asbestos forests."

LP2—closed canopy stands between 150-300 years old, tend to be difficult to burn under "normal" fire conditions. These tend to be even aged stands, not so many large trees, snags or course woody debris, at least compared to the next cover type.
Finally, when you get to LP3—300+ year old stands, have ragged canopies with lots of woody debris. They tend to burn quite readily in even moderately dry conditions (Despain 1990).

Outcomes of three studies projecting the future of Lodgepole Pine
Northern Rockies Adaptation Partnership: (Halofsky et al. 2018)
Area: USFS R1 (MT, northern ID, Western SD) and the Greater Yellowtone Area
Methods: Used MC2 DVM—a course scale dynamic vegetation model—to simulate fire-veg interactions in response to climate change across space and time
Results (for 2050ish)

- **LP is expected to both expand and contract in range, but as long as fire remains on the landscape, the species is likely to maintain its presence in the Northern Rockies at roughly the same proportions as during the last 100 years, albeit in different areas**

Key uncertainties and Assumptions

- SCALE (large scale might make this assessment less relevant to the specific GYA landscape)
- GCM Uncertainty (in all three assessments)
- Interactions among climate, vegetation, and disturbance, and interactions among different disturbance regimes

Pielielek et al. 2015
Methods

- Area: Entire GYA
- Species Distribution Model (Climate Niche)
- Projected future (a) Core Habitat (b) deteriorating habitat; and (c) expanding habitat
- Used dynamic water balance to improve projections

Assumptions

- Present distribution captures species climate tolerances
- Other factors (eg. Disturbance) play minor role

Results

- **PICO loss 26-28% by 2040; 42-53% by 2070; 50-85% by 2100**
- **Distribution shift**

Key uncertainties

- Doug Fir: expanded into LP in RCP 4.5; not in 8.5. Uncertainty regarding rhyolitic soils
- Poor model performance and disagreement among GCMs led to substantial variation in the LP results

Clark et al. 2017
Methods

- Area: YELL Central Plateau (~20% of the park)
- Used FireBGCv2—a dynamic, spatially explicit ecosystem process model—to simulate fire-veg interactions in response to climate change across space and time
- Projected 2050 (a) forest structure and composition with changing climate; (b) effects of interactions of climate and fire; and (c) future vegetation and fire regimes

- Used 2 climate scenarios (a) A2-low (+1.6° +13%P) (b) A2 Ensemble Avg (+2.7 ° +5%P) (c) A2-high (+4 +3%)

Results (for 2050ish)

- **PICO % basal area loss 24% (low); 17% (Avg); 43% (high) (historic 71% of basal area)**
- **Doug Fir gain % basal area 6%, 26%, 62% (historic 3%)**

Key uncertainties and Assumptions

- Doug fir cannot compete on rhyolitic soils under current climate but paleo evidence suggests great abundance of DF ~9000 ago
- Assumed 20% serotiny; model is used to simulate changes in veg fire regimes NOT predict what will happen

LP and Fire

Westerling et al in 2006 looked HISTORCAL data (not projected) and found a large difference in wildires between the periods 1970-1986 and 1987-2003:

- Increase in the length of fire season (78 days)
- 4-fold increase in number of big fires
- 6.7 – fold increase in area burned
- 5-fold increase in the time it took to put out a fire
- Clearly, something was afoot

Westerling (2016) updated that information in a General Technical Report for the USFS in 2014 and found a similar pattern in frequency and area burned of large fires by decade and states.

- Bottom line: Large fires in the last decade were 480% more frequent and burned 930% more area than in the first decade.

Specific to the GYA, Westerling et al. 2011 found that:

- All models predicted substantial increases in fire by midcentury, with fire rotation (the time to burn an area equal to the landscape area) reduced to <30 y from the historical 100–300 y for most of the GYE.
- Years without large fires were common historically but are expected to become rare as annual area burned and the frequency of regionally synchronous fires increase.
- Findings suggest a shift to novel fire–climate– vegetation relationships in Greater Yellowstone by midcentury because fire frequency and extent would be inconsistent with persistence of the current suite of conifer species.
- The predicted new fire regime would transform the flora, fauna, and ecosystem processes in this landscape and may indicate similar changes for other subalpine forests.

Conclusion

- The two projections specific to the GYA and Yellowstone National Park project decreased abundance and distribution of LP by mid-century and further increases by end-of-century.
- Surviving LP could be maintained in the earlier successional stages through more frequent fire.
- Douglas fir is likely to expand its range into area that is now LP
- Increases in fire could portend novel climate-fire-vegetation relationships.

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Douglas fir/Aspen -Andy Hansen

Historical and current distribution and spatial patterns. The distributions and abundances of Douglas fir (*Pseudotsuga menziesii*) and Aspen (*Populus tremuloides*) have likely changed substantially since the Little Ice Age, in part due to the changing fire regimes. Gallant et al. 2003 backdated stands based on age to reconstruct landscape pattern in the East Beaver Creek in the Centennial Mountains of Idaho for the period 1985-1996. Results indicated that the area was dominated by Aspen and Aspen/conifer stands in the earlier time period and by conifer forests in the later period. This is consistent with fire history studies indicating frequent burning in the mid 1800s associated with initial European settlement and fire exclusion thereafter. Aspen was likely favored by the initial fires and then reduced in the following decades by competition from Douglas fir. Similar patterns were found in stratified random aerial photo samples from across the GYE by Powell and Hansen (2007) and Brown et al. (2006). Conifer distribution and canopy density increased during 1970 to 1999, particularly at lower treeline on east facing slopes. This was likely due to fire exclusion, among other factors. Aspen cover declined across most samples during 1956-2001, with competition from conifer a significant predictor. Fire frequency has increased since 1987, with the large fires in 1988 followed by substantial fires in subsequent years. The 1988 fires favored aspen regeneration in a study are in Yellowstone National Park (YNP), initially in warmer sites and in more recent years in cooler sites in conjunction with the ca 1 ^{0}C warming since if 1988 (Hansen et al. 2016). The extent to which fires in recent decades has released aspen from conifer completion around the GYE has not been measured, but may be substantial.

Future Projections. Projections under future climate scenarios were done with species distribution models (SDMs) and mechanistic models. SDMs quantify the climate and soil characteristics of places currently occupied by a species and then are used to map change in the locations of suitable habitats under climate scenarios. They consider only the climate and soil habitat requirements of the species and not dispersal, population dynamics, disturbance, species interactions or other factors. Using this approach, Piekielek et al. (2015) projected that Douglas fir would lose suitable habitat in the lower elevations of its current distribution and gain suitable habitat in settings now occupied by lodgepole pine (*Pinus contorta*). The projected change in areal extent in suitable habitat from present by 2040 was -35-37% under the RCP 4.5 and 8.5 scenarios. Change in the locations or total area of suitable habitat of aspen were minimal for aspen by 2040 under the two climate scenarios.

A field experiment of Douglas fir establishment rates (Hansen et al. In Revision) confirmed that Douglas fir is sensitive to the warmer soil temperatures at its lower distributions and are consistent with the projection of those habitats becoming unsuitable under projected warming.

Mechanistic models attempt to the multiple types of factors that are known to influence vegetation response to climate change. Simulation studies by Clark et al. 2016 using the FireBGC mechanistic model and by Hansen et al. (2018) using the ILAND mechanistic model both project Douglas fir expanding in dominance over lodgepole pine on the Yellowstone Plateau consistent with the SDM results for that mid forest elevation zone.

Uncertainty. Levels of uncertainty in SDM and mechanistic model projections for these species is high due to uncertainty in future climates, the simpler formulation of the SDM approach, and compounded error in the several processes simulated by the mechanist models.

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Sagebrush/Juniper -Katie Renwick

Historical and current distribution and spatial patterns. Big sagebrush (*Artemisia tridentate)* is common throughout the western United States. The boundaries of its distribution are likely similar to what they would have been historically, but land use change (development, agriculture, and oil and gas development) have eroded parts of its range. In some areas where sagebrush still exists it is no longer the dominant species due to juniper encroachment resulting from a history of fire suppression. Across the GYE, *Artemisia tridentate ssp. Vaseyana* is the most common subspecies.

Future Projections. Projections of future sagebush distribution have provided somewhat mixed results. A species distribution model for *Artemisia tridentate ssp. Wyomingensis* predicted large declines, particularly in the southern portion of its range, though populations in the GYE were predicted to persist (Still & Richardson 2015). A seedling survival model predicted that conditions would become unfavorable for sagebrush establishment in many areas near the species' range margins (Schlaepfer et al. 2012). One study that compared four different models, however, found that many populations of sagebrush may be unaffected by climate change or even experience slight increases in abundance (Renwick et al. 2017). Experimental evidence of sagebrush response to climate change is also mixed, suggesting that response will likely vary based on local factors including the underlying climate and soil moisture regime.

Uncertainty. Model results tend to involve a high level of uncertainty related to the choice of model, input data, and uncertainty in climate projections. Uncertainty may be less in certain locations. Most models agree that sagebrush populations in areas that are very hot and dry will likely decline, potentially resulting in extirpation. Similarly, most evidence suggests that sagebrush populations will either remain stable or even grow in areas that are relatively cool and moist compared to the mean across its entire range.

Appendix II. Projected change from Desired Condition for cover types within the Warm, Dry PVT.

Key Characteristics	Potential Climate Impacts			
	Desired Range	**Existing**	**Expected change from desired condition**	**Direction fo change from desired condition**
Cover Type (areal extent, % of area)				
Aspen	1-5	2 (1-5)	Stay within or relatively stable	Increase
Douglas-fir	70-90	49 (41-57)	Away	Decrease
Lodgepole Pine	5-10	8 (4-13)	Stay within or relatively stable	Decrease
Transitional-Grass/Forb/Shrub	1-20	30 (22-38)	Away	Increase
Tree Size Class				
Transitional-Grass/Forb/Shrub	5-14	30 (22-38)	Away	Increase
Seedling and Sapling (<5" DBH)	6-17	7 (4-11)	Stay within or relatively stable	Increase
Small Tree (5-9.9" DBH)	6-16	20 (14-26)	Away	Increase
Medium Tree (10-14.9" DBH)	13-36	27 (20-34)	Stay within or relatively stable	Decrease
Large tree (15"+ DBH)	27-74	15 (10-21)	Away	Decrease
Density Class				
Low (<40% canopy cover)	25-60	35	Stay within or relatively stable	Increase
Medium (40-60% canopy cover)	35-55	19	Away	Decrease
High (>60% canopy cover)	1-20	46	Toward	Decrease

Appendix III. Projected change from Desired Condition for cover types within the Cool, Moist PVT.

Key Characteristics	Potential Climate Impacts			
	Desired Range	**Existing**	**Expected change from desired condition**	**Direction of change from desired condition**
Species Presence (areal extent, % of area)				
Lodgepole Pine	40-60	30 (24-37)	Away	Decrease
Mixed Mesic Conifer	15-30	20 (14-25)	Stay within or relatively stable	Increase in DF
Transitional-Grass/Forb/Shrub	1-5	18 (13-23)	Away	Increase
Spruce/Fir	15-35	26 (20-31)	Away	Decrease
Whitebark Pine	1-5	2 (0-3)	Stay within or relatively stable	Decrease
Tree Size Class				
Transitional-Grass/Forb/Shrub	1-7	18 (13-23)	Away	Increase
Seedling and Sapling (<5" DBH)	7-36	14 (10-18)	Stay within or relatively stable	Increase
Small Tree (5-9.9" DBH)	8-40	25 (19-30)	Stay within or relatively stable	Increase
Medium Tree (10-14.9" DBH)	12-61	27 (22-33)	Stay within or relatively stable	Increase
Large tree (15"+ DBH)	8-40	15 (10-19)	Stay within or relatively stable	Decrease
Density Class				

Low (<40% canopy cover)	10-40	19	Stay within or relatively stable
Medium (40-60% canopy cover)	40-60	18	Unknown
High (>60% canopy cover)	15-40	63	Unknown

Appendix IV. Projected change from Desired Condition for cover types within the Cold PVT.

Key Characteristics	Potential Climate Impacts			
	Desired Range	**Existing**	**Expected change from desired condition**	**Direction of change from desired condition**
Species Presence (areal extent, % of area)				
Lodgepole Pine	40-60	30 (24-37)	Away	Decrease
Mixed Mesic Conifer	15-30	20 (14-25)	Stay within or relatively stable	Increase in DF
Transitional-Grass/Forb/Shrub	1-5	18 (13-23)	Away	Increase
Spruce/Fir	15-35	26 (20-31)	Away	Decrease
Whitebark Pine	1-5	2 (0-3)	Stay within or relatively stable	Decrease
Tree Size Class				
Transitional-Grass/Forb/Shrub	1-7	18 (13-23)	Away	Increase
Seedling and Sapling (<5" DBH)	7-36	14 (10-18)	Stay within or relatively stable	Increase
Small Tree (5-9.9" DBH)	8-40	25 (19-30)	Stay within or relatively stable	Increase
Medium Tree (10-14.9" DBH)	12-61	27 (22-33)	Stay within or relatively stable	Increase
Large tree (15"+ DBH)	8-40	15 (10-19)	Stay within or relatively stable	Decrease
Density Class				
Low (<40% canopy cover)	10-40	19	Stay within or relatively stable	
Medium (40-60% canopy cover)	40-60	18	Unknown	
High (>60% canopy cover)	15-40	63	Unknown	