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Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates

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Abstract
Many US forest managers have used historical ecology information to assist in the development of desired conditions. While there are many important lessons to learn from the past, we believe that we cannot rely on past forest conditions to provide us with blueprints for future management. To respond to this uncertainty, managers will be challenged to integrate adaptation strategies into plans in response to changing climates. Adaptive strategies include *resistance* options, *resilience* options, *response* options, and *realignment* options. Our objectives are to present ideas that could be useful in developing plans under changing climates that could be applicable to forests with Mediterranean climates. We believe that managing for species persistence at the broad ecoregion scale is the most appropriate goal when considering the effects of changing climates. Such a goal relaxes expectations that current species ranges will remain constant, or that population abundances, distribution, species compositions and dominances should remain stable. Allowing fundamental ecosystem processes to operate within forested landscapes will be critical. Management and political institutions will have to acknowledge and embrace uncertainty in the future since we are moving into a time period with few analogs and inevitably, there will be surprises.

Keywords: climate change, historical variability, restoration, forest policy, Sierra Nevada, Sierra San Pedro Martir, mixed conifer, Jeffrey pine, ponderosa pine, upper montane

1. Introduction

Anthropogenic inputs of greenhouse gasses and natural climate variation will continue to change the Earth's climate in the coming decades. While 'climate change' typically connotes 21st-century global warming, the larger context of climate as an ecosystem architect should be assimilated into resource-science thinking. In the past two decades, new tools, new theory, and a critical mass of empirical research have revolutionized understanding of Earth's climate system. Historic climate is now understood as being far more variable and complex than previously imagined (Ruddiman 2001). Several key insights have emerged. First, climate naturally *changes* over time and the changes *cycle*, or *oscillate*, rather

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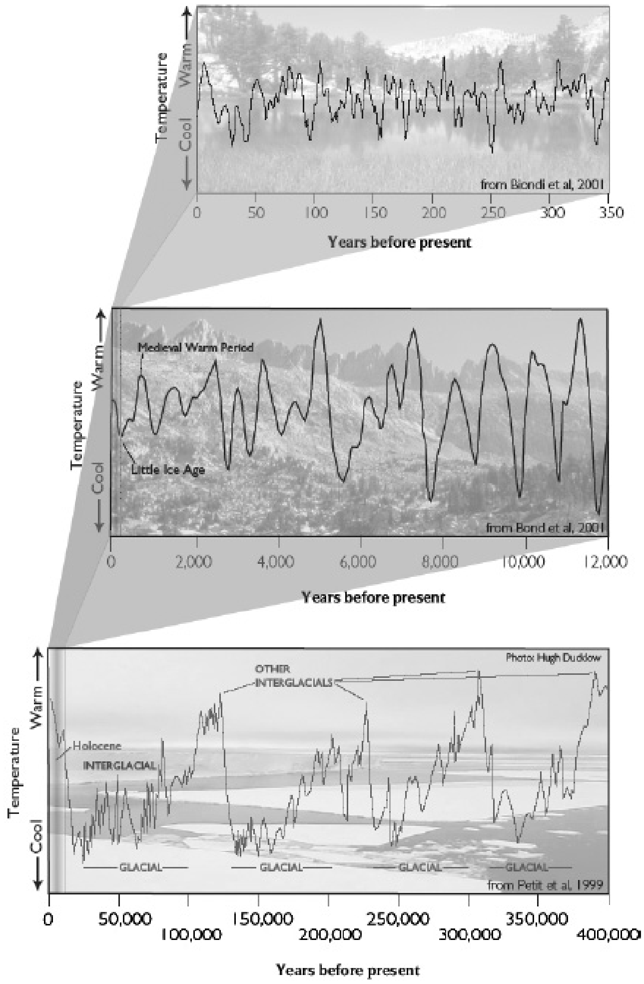

Figure 1. Nested temperature cycles at decadal (top; Pacific Decadal Oscillation), century (middle; Bond cycles), and millennial (bottom; Milankovitch cycles) scales. Cycles are driven by different mechanisms; decadal by ocean circulation and sea temperature, century by solar variability, and millennial by changes in Earth's orbit around the sun. These and other cycles interact continually and, in combination, result in ongoing gradual and abrupt changes in Earth's natural climate system. From Rosenthal and Millar (2003).

than wander stochastically or follow pervasive linear trends (figure 1). It is important when considering 21st-century climate change to recognize that change itself is natural and has precedent. However, the current effect of anthropogenic forcing on the cumulative climate signal is unknown since we have no analog in the past for the present situation.

In the last two decades many US forest managers have used historical ecology information to assist in the development of desired conditions (Landres *et al* 1999, Swetnam *et al* 1999, Millar and Woolfenden 1999a, 1999b). In the case of the US National Park Service (NPS), past forest conditions have been used as a target for restoring the 'natural' conditions called for by NPS policy (NPS 1988, Stephenson 1999). In the US Forest Service (USFS), past forest conditions have been used to guide timber harvesting practices in the last 1–2 decades, so that the scale and intensity of logging comes as close as possible to mimicking the effects of presettlement forest dynamics (Manley *et al* 1995, Weatherspoon 1996). In both cases, an underlying premise is that by maintaining forest conditions within the range of pre-Euro-American conditions, managers are most likely to sustainably maintain forests—including their goods, ecosystem services, and biodiversity—into the future.

While there are many important lessons to learn from the past, we believe that we cannot rely on past forest conditions to provide us with blueprints for current and future management (Millar *et al* 2007). In particular, the nature and scale of past variability in climate and forest conditions, coupled with our imprecise ability to fully reconstruct those conditions, introduce a number of conceptual and practical problems (Millar and Woolfenden 1999a). Detailed reconstructions of historical forest conditions, often dendroecologically based, are very useful but represent a relatively narrow window of time and tend to coincide with tree recruitment in the generally cooler period referred to as the little ice age (figure 1). As such, manipulation of current forests to resemble past conditions may not produce the desired result when considering future climates.

Restoration of forest structure to resemble those of the past provides no guarantee of sustainability into the future. However restoring the process that shaped forests historically for millennia can provide some degree of assurance in maintaining fire-adapted forests (Fulé 2008). This is especially true when considering already observed increases in fire occurrence (Westerling *et al* 2006) and fire severity (Miller *et al* 2009) since the early 1980s, as well as anticipated increases in wildfire under future climate scenarios (McKenzie *et al* 2004, Flannigan *et al* 2005).

An important additional element of uncertainty derives from the interaction of climatic variability with anthropogenic stressors such as air and water contaminants, invasive species, land development and fragmentation, and exceedingly high levels of atmospheric carbon dioxide. The confounding influences of these novel and multiple stressors create non-analog situations where the present is unlike any past period.

To respond to this uncertainty, managers will be challenged to integrate adaptation strategies (actions that help ecosystems accommodate changes) into overall plans in response to changing climate. Adaptive strategies include *resistance* options (forestall impacts and protect highly valued resources), *resilience* options (improve the capacity of ecosystems to return to desired conditions after disturbance), *response* options (facilitate transition of ecosystems from current to new conditions), and *realignment* options (modifying forests to present and/or future conditions and restoring key ecosystem processes). In many cases management actions will include two or more of these adaptive strategies.

In this letter our objective is to provide a general framework and present tactical applications that could be useful in developing operational forest plans under changing climates. We apply and expand on the 'conceptual framework' developed by Millar *et al* (2007) for managing Mediterranean forests under changing climates using areas in California (USA) and Baja California (Mexico). While our examples come from forests in California and Baja California some of the principles given should be applicable to a broad range of forests that once experienced frequent, low-moderate intensity fire regimes.

2. Forest descriptions

2.1. Forests in California, USA, and Baja California, Mexico

We use mixed conifer forest and subalpine and alpine vegetation types as examples to discuss what *managing forests under changing climates* might entail. Vegetation types in the Sierra Nevada, the mountains of southern California, and the Sierra San Pedro Martir (SSPM), Mexico, range from *Quercus* woodlands and chaparral shrublands in the foothills, through coniferous forests in the montane and subalpine zones (dominated especially by *Abies* and *Pinus*), to diverse herbaceous alpine communities. The subalpine and alpine zones in the California portions of these mountains are noted for their deep canyons, high plateaus, and meadows. Climates in these regions are Mediterranean with warm dry summers and cold wet winters although SSPM forests do receive more summer precipitation than similar forests in California (Stephens *et al* 2003, Skinner *et al* 2008).

Management histories have varied greatly in these forests in California and Baja California. California forests have experienced approximately 100 years of fire exclusion and many have been harvested using even-aged systems early in the 1900s followed by a diverse group of silvicultural operations (Laudenslayer and Darr 1990). Fire exclusion has resulted in increased tree densities in Sierra Nevada mixed conifer, ponderosa pine, and Jeffrey pine forests and a reduction in shade intolerant species (Parsons and DeBenedetti 1979, North *et al* 2007). In southern California, tree densities in mixed Jeffrey pine forests in the San Bernardino Mountains have increased by 79% from the early 1930s to 1992 (Minnich *et al* 1995) and more than doubled at Cuyamaca Mountain (Goforth and Minnich 2008) primarily by the effects of fire suppression. The combination of past management actions in these California forests has produced high fire hazards over broad spatial scales.

In contrast to California forests, forests in the SSPM have experienced a very different management history. The isolated SSPM is unique within the California floristic province in that its forests have received very little harvesting and fire suppression did not begin until the 1970s (Stephens *et al* 2003). Median fire return intervals in Jeffrey pine-mixed conifer forests in the SSPM are shorter than 15 years and this is comparable to past fire frequency in similar forests in the Sierra Nevada and southern California (Skinner and Chang 1996, Taylor and Beaty 2005, Everett 2008). The seasonality of past fires, inferred from intra-ring scar positions, in the SSPM differs from that in California with the majority of fires recorded in the earlywood portion of annual ring, most fires in Californian forests are recorded in the latewood or dormant periods (Stephens *et al* 2003). Although the SSPM has been grazed to varying levels of intensity, the absence of large-scale fire suppression and harvesting suggests these forests may provide information useful to characterize intact forests that continue to respond to disturbance regimes and changing climate.

3. Discussion

3.1. Adaptive strategies—increasing resiliency

One set of adaptive options is to promote resilient forested ecosystems. Resilient forests are those that not only accommodate gradual changes related to climate but tend to return toward a prior condition after disturbance either naturally or with management assistance. Promoting resilience is the most commonly suggested adaptive option discussed in a climate change context (Hansen *et al* 2003). The coniferous forests in the SSPM are an example of a resilient forest. From 1999 to 2002 a severe drought occurred in the SSPM and forests in southern California (Stephens and Fulé 2005). In the SSPM forests approximately 1 new snag ha^{-1} was created by native insects and diseases but overall forest mortality was very low (Stephens and Gill 2005). Following this severe drought, a 2003 wildfire occurred that only produced moderate fire effects with only 20% tree mortality and high number of seedlings surviving (Stephens *et al* 2008) emphasizing that this forest was able to return to a state very similar to its previous condition even after severe stresses.

Why were the forests in the SSPM able to incorporate drought, insects, and wildfire without producing mortality outside of a desired range? Research suggests that heterogeneity in spatial patterns of forest structure and fuels are critical (Stephens *et al* 2008). High spatial variability characterizes all live tree, snag, fuel, coarse woody debris, tree regeneration, and canopy cover in the forests of the SSPM without recent fire (Stephens and Gill 2005, Stephens *et al* 2007). Before the 2003 wildfire seedlings and trees were spatially clumped or randomly distributed, respectively, after the wildfire these spatial patterns were maintained (Stephens *et al* 2008). High variability in surface fuels and forest structure produced equally diverse fire behavior and effects, maintaining high spatial heterogeneity when the forest burned under a frequent fire regime.

Spatial variability in forest structure is a key element in these resilient forests and heterogeneity should be included in US forest management efforts (Stephens and Fulé 2005). However, spatial variability is uncommon in most US forest restoration practices (North *et al* 2009). The most common forest fuel reduction treatment in western US forests is a thin-from-below to separate overstory tree crowns and maintain a desired basal area within a limited range (Graham *et al* 2004). These practices produce relatively uniform forest conditions over broad areas and are in strong contrast to what is found in the resilient SSPM forests.

In similar forests in southern California the multi-year drought (1999–2002) killed millions of trees (Stephens and Fulé 2005). Where wildfire impacted mixed Jeffrey pine forests in southern California mortality was very high. In the Laguna Mountains in the San Diego County, tree mortality varied from 40 to 95% after the 2003 Cedar Fire (Franklin *et al* 2006). Fire caused similar damage to mixed conifer forests at Cuyamaca Mountain (Goforth and Minnich 2008). In contrast, frequent fire until the 1970s and no harvesting has allowed the resilient SSPM forests to incorporate disturbance without

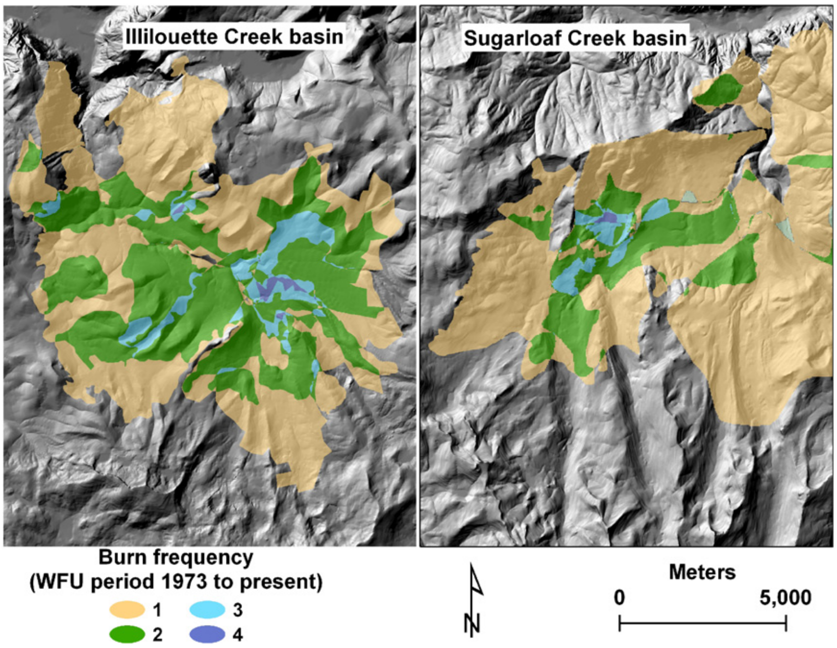

Figure 2. Frequency of fire occurrence in two managed wildfire areas within the Sierra Nevada, California, USA. Since 1973 nineteen managed fires (>40 ha) have occurred in the Illilouette Creek basin (Yosemite National Park), and 12 have occurred in the Sugarloaf Creek basin (Sequoia-Kings Canyon National Park).

wide-scale tree mortality and to maintain tree regeneration (Stephens *et al* 2008).

There are some noted examples where the use of fire alone appears to have successfully promoted spatial heterogeneity and ultimately resilient forests. In two different upper elevation Sierra Nevada mixed conifer forests that have experienced ca. 30 years of using managed, naturally ignited wildland fires (figure 2), the proportion of stand replacing fire in recent large fires was very low (3–12%) (Collins *et al* 2007). Based on field data (Collins 2004) and satellite-derived images of fire severity (Collins *et al* 2009, 2010) these large fires created a high degree of spatial heterogeneity both within individual forest stands and across the landscape. In addition Collins *et al* (2009) demonstrated that the proportion of stand replacing fire throughout the ca. 30 years of managed fires did not significantly change, despite significantly increasing trends in stand replacing fire throughout Sierra Nevada mixed conifer forests reported by Miller *et al* (2009). This stability in fire effects over time suggests high resiliency. It is likely that there are many other remote forests throughout the western US where allowing more lightning-ignited fires to burn during appropriate conditions would increase resiliency. Certainly challenges exist regarding increasing the area burned by managed wildland fire including smoke production and the risk of fires burning outside desired boundaries. Uncertainty in future climates will necessitate that managers and the interested public accept higher variation in fire behavior and effects when managing both prescribed and wildland fires. The status quo of primarily focusing on fire suppression policies will inevitably result in large, high severity wildfires that will not conserve many of the values that managers and the public desire from forests (high quality water, aesthetics, wildlife habitat for many species, recreation, carbon sequestration).

3.2. Increasing resistance

Another adaptive option is to manage forest ecosystems and resources so that they are better able to resist the influence of climate change or to forestall undesired effects of change (Parker *et al* 2000). Most mixed conifer forests in the Sierra Nevada and southern California are vulnerable to high severity wildfire (Westerling and Bryant 2008, Miller *et al* 2009) and several federal laws have been created in the US to address this critical land management issue (Stephens and Ruth 2005).

In forests that once experienced frequent, low-moderate intensity fire regimes, reduction of surface and ladder fuels can create forests with high resistance to wildfire (van Wagtendonk 1996, Agee and Skinner 2005, North *et al* 2007, Stephens *et al* 2009). Therefore, increased use of appropriately designed fuels treatments (Agee and Skinner 2005) is recommended in accessible mixed conifer, ponderosa pine, and Jeffrey pine forests in the Sierra Nevada and southern California. Strategically placed landscape area treatments (SPLATs—Finney 2001), or any other coordinated landscape fuel treatments designed to minimize the area burned by high intensity head-fires, may be an effective strategy to reduce fire severity in large, heterogeneous areas (Collins *et al* 2010).

Fuels treatments including the use of prescribed fire without any pre-treatment are the most common treatment in US National Parks in the Sierra Nevada (Sequoia-Kings Canyon and Yosemite National Parks) and Lassen National Park in the Southern Cascades. These parks have reduced fire hazards and reintroduced fire as an ecosystem process since the late 1960s with management ignited prescribed fires (Kilgore 1974). Such fires increase forest resistance and also allow the most common ecosystem process to continue to influence plant and animal populations. Limited burning windows (mostly 5–7 days in length) commonly result in burning crews pushing fires to complete them in the short time allotted. Allowing longer burning periods with less intense ignition patterns would lead to increased variability in fire behavior and effects. The main constraint from increased use of prescribed fires is smoke production that is regulated by air quality agencies. Smoke from forest fires (of desired severity and size) is a natural ecosystem component, and regulations should be adapted to allow more burning opportunities while also considering public health (Stephens and Ruth 2005). In contrast, large and intense wildfires produce extreme amounts of smoke that can inundate large areas for weeks or months, producing a variety of effects and unwanted impacts. The costs of conducting prescribed fires or managing wildland fires from a public health standpoint should be weighed against the benefits of avoiding the exacerbated, and often prolonged effects associated with large and intense wildfires.

The US Forest Service has primarily used mechanical fuel treatments, with and without prescribed fire, to increase forest resistance in Sierra Nevada and southern California forests. One of the largest such efforts in the US has occurred in the northern Sierra Nevada and is known as the ‘Quincy Library Group’ lands which have used a system of Defensible Fuel Profile Zones (DFPZs) in an effort to reduce fire hazards and enhance fire suppression. While there has been considerable debate surrounding this management plan it has successfully treated approximately 20 000 ha of forests since 2000 (Dillingham 2010, Moghaddas *et al* 2010). While DFPZs are still heavily dependent on fire suppression tactics and personal (Agee *et al* 2000), they have been successfully used to manage some wildfires in this area (Moghaddas and Craggs 2007). Increasing the area treated with appropriately designed and situated fuel treatments in forests in the Sierra Nevada and southern California will increase their resistance to fire, and secondarily, to tree-killing insects.

3.3. Facilitate transitions—responses

The third adaptation option is to facilitate transitions of ecosystems from current to new conditions, that is, to promote successful responses to climate. To assist, or enable ongoing natural adaptive processes such as species dispersal and migration, population mortality and colonization, changes in species’ dominances and community composition, and changing disturbance regimes, forest plans should address large spatial scales. The strategic goal is to encourage gradual adaptation and transition to inevitable change, and thereby to avoid rapid threshold responses that may occur otherwise. Allowing fundamental ecosystem processes to operate within these landscapes is critical to facilitate transitions.

Operationally managing for uncertainty at the landscape scale (>10 000 ha) translates to maintaining species persistence within a large ecoregion. In the Sierra Nevada, we propose that maintaining the richness of native species presently within the boundaries of the Sierra Nevada ecoregion (see SNEP 1996 for boundaries) could become the overarching management goal. This, however, does not mean to enforce the maintenance of current species range limits, population distributions, abundances, plant community types, wildlife guilds, etc. Further, it is a philosophy that recognizes changes in fire regimes, forest mortality and colonization events, and in some cases type conversions may occur.

Paleorecords in areas where abundant information exists can be used as a test of what has been sustained naturally over time. When Quaternary vegetation records from the Sierra Nevada were assessed, Millar and Woolfenden (1999b) found that only a few conditions often associated with ecological sustainability concepts pertained. These included: (1) relative stability of the Sierra Nevada ecoregion, i.e., persistence of a distinct ecoregion over time, and, (2) persistence of overall species diversity at the scale of the entire Sierra Nevada ecoregion, with only one species, a spruce (*Picea* spp.), disappearing from the region about 500 000 years ago. Beyond these two features, however, other conditions commonly associated with ecological sustainability did not occur.

At sub-regional scales within the Sierra Nevada, species diversity changed considerably at timescales of centuries to millennia. Movement of individual species meant that vegetation assemblages changed over time and/or shifted locations as species followed climate gradients individualistically (Woolfenden 1996). Vegetation communities appeared sometimes to shift locations, when individual species tracked climate coincidentally, and in other cases, changed composition and dominance relations as species responded differently. Non-analog communities occurred transiently, such as the co-occurrence 20–30 thousand years ago in the southern Sierra Nevada of yucca (*Yucca brevifolia*) and Utah juniper (*Juniperus osteosperma*) with an understory of *Artemesia tridentata*, *Purshia tridentata*, and *Atriplex concertifolia* (Koehler and Anderson 1995). Finally, historic fire regimes reconstructed from the Sierra Nevada have changed over time at multiple scales (Swetnam 1993); however we recognize that the largest change in Sierra Nevada fire regimes occurred with the onset of fire suppression in the early 20th-century.

These and similar records challenge interpretations of ecological sustainability that emphasize persistence of population sizes and species abundances, stability of native distribution ranges, and continuity of vegetation and wildlife community compositions. By contrast, we find that, of the diverse concepts commonly associated with ecological sustainability, only native species persistence within large ecoregional boundaries, such as the Sierra Nevada, pertains. Our goal here is not to imply that any combination of species would be acceptable in Sierra Nevada forests but that managers should not attempt to maintain all species at their present locations, as climate continue to change this will probably not be possible or desirable.

Another application of facilitating transitions in response to changing climates occurs during reforestation after high severity wildfires and timber harvesting. The area burned by high severity wildfire in mixed conifer forests has increased in the Sierra Nevada and southern Cascades Mountains from 1984 to 2006 (Miller *et al* 2009). Mixed conifer tree species do not have a canopy-stored (e.g., serotiny) seed bank which reduces their resiliency to large, severe fire disturbances. As Miller *et al* (2009) demonstrated, continuous patches of stand replacing or stand removal fire have been increasing, which are causing mortality of mixed conifer tree species at spatial scales larger than can be naturally regenerated in the next century.

Artificial regeneration is commonly used to reforest portions of high severity wildfires and clear-cut harvesting units. The most common tree planting pattern is a grid with 4–6 m spacing and a single tree species is planted. This planting pattern produces relatively uniform forest conditions that can be susceptible to wildfire (Weatherspoon and Skinner 1995, Odion *et al* 2004, Kobziar *et al* 2009) and other disturbances. Planting seedlings of multiple species in clusters (2–3 seedlings over an 5 m × 5 m area) at wide and variable spacing (7–15 m) would produce higher spatial heterogeneity versus the standard grid pattern, and require less maintenance (e.g., pre-commercial thinning) as the forest stands develop (Tompkins 2007). This facilitated response to new forest establishment would increase spatial heterogeneity in tree patterns which should increase resistance and resiliency. An alternative would be to regenerate areas using a standard grid pattern and the use variable density thinning to develop spatial heterogeneity in the developing forest.

While in the past several decades, genetic guidelines for reforestation have been increasingly refined to favor local germplasm, relaxing these guidelines may be appropriate under changing climates (Millar *et al* 2007). While 'local' remains important, planting stock choices may be expanded to include a proportion of germplasm from adjacent seedzones rather than all from a local seedzone; seedzone sizes and transfer rules may be broadened; and redundancy of germplasm over a range of sites increased. These reforestation ideas are supported by findings from an innovative modeling effort intended to optimally select a set of seed sources for regenerating forests under a range of future climate scenarios (Crowe and Parker 2008).

3.4. Realignment options

In most California forests past management activities have significantly changed forest structure, particularly in forests that once experienced frequent, low-moderate intensity fire regimes. Early logging operations removed the largest, most economically desirable species (Laudenslayer and Darr 1990). Early settlement era fires and fire suppression have further altered the vertical and horizontal structure of mixed conifer forests to be more uniform (North *et al* 2009). A realignment option could be designed to begin to restore critical structural heterogeneity in forest structure. Realigning forests implies modifying forests to present and/or future conditions which can be quite different from the past.

Restoration of historic conditions, while not the over-arching goal of forest management, could still be useful in producing conditions that are much better than the majority current conditions. Restoration of patterns of burning and fuels/forest structure that reasonably emulate historical conditions prior to fire exclusion is consistent with reducing the vulnerability of these ecosystems to loss (Allen *et al* 2002, Falk 2006). Restoration treatments can also enhance the biodiversity of understory plant communities (Wayman and North 2007).

Restoration of fire-adapted forests does not present an either/or situation; it is unlikely that a comprehensive blanket approach to management can or should be devised (Fulé 2008). However, as we move into a more fire-prone environment, it is logical to use fire and fire-related characteristics of structure and composition to enhance resistance to loss. As Fulé (2008) writes many restorationists have had a naive reliance on ecosystem stability that is appropriately being challenged by paleoecological and field ecology evidence (Harris *et al* 2006). Yet even as we recognize that a broader, longer, more variable, and more functional perspective on reference conditions reduces the perception of stability, it is important to bear in mind that native ecosystems are not necessarily fragile (Fulé 2008).

Since the last glacial period, fire-adapted pines of North America have occupied a vast range encompassing monsoonal, Mediterranean, and continental climates with an extraordinary diversity of soils, geomorphological types, and associated plant and animal species. These forests have already exhibited great flexibility and adaptation. Thoughtful restoration of the ecological role of fire and fire-related structure and composition should enhance the chances of persistence of some of these native forests under future climate conditions (Fulé 2008).

A final realignment option would be the establishment of refugia. These could be considered part of an integrated strategy to balance other 'response' actions such as assisted migration. Sierra Nevada yellow-legged frog (*Rana sierrae*) is a rare species of concern in the forests of the Sierra Nevada that has declined throughout its range. A possible management option would be to designate networks of high elevation lakes that have connectivity among them, exotic trout removed, and native frogs introduced (Lacan *et al* 2008).

3.5. Integrating responses

Decisions about appropriate strategies and treatments are best resolved after the effects of climate change have been reviewed and project priorities have been ranked. Appropriate treatments are determined by the conditions and context of the resource; social and ecological values; timescales for management; and feasible goals for treatment relative to climate effects and are thus determined in formal assessment processes for large scales (e.g., US federal Land Management Planning). Adaptation literature most commonly focuses on resilience as a primary goal to address these factors (Hansen *et al* 2003). We expanded this framework to address potential adaptation strategies that fit one or more of the following objectives: resistance, resilience, response, and realignment (Joyce *et al* 2008). These four categories encourage thinking about the range of possible options and do not imply that a treatment fits into one specific category. Some treatments may reflect only one strategy, and others may combine them. The overriding objective is to construct effective management solutions that best fit the situation at hand.

3.6. Integrated response example on US federal lands

The US Global Change Research Program, formerly the Climate Change Science Program, prepares synthesis and adaptation products (SAPs) to support policy and decision-making related to climate change on lands administered by thirteen US federal agencies. The SAP 4.4 reports published in 2008 reviewed management adaptations for climate-sensitive ecosystems and resources across a range of federally managed lands and waters including national parks, national forests, fish and wildlife refuges, wild and scenic rivers, marine protected areas, and coastal estuaries. The studies sought to provide practical information on potential adaptation options for resource managers by asking: (1) how will climate change affect the ability of resource managers to achieve their management goals? And (2) what might a resource manager do to prepare the management system for climate change impacts while maintaining current goals (and constantly evaluating if these goals need to be modified or re-prioritized)?

National forests administered by the USDA Forest Service are the subject of SAP 4.4 chapter 3 (Joyce *et al* 2008). Under the auspices of this project, case studies of climate adaptation were conducted on three national forests in the US, the Tahoe National Forest (TNF) in California, Olympic National Forest in Washington, and Uwharrie National Forest in North Carolina. The case studies sought to investigate current status of resource management relative to climate concerns, including proactive measures currently in practice, barriers and opportunities for incorporating climate, and needs for the future.

The TNF, situated in the northern Sierra Nevada and straddling the range crest, is typical of western US national forests where productive and commercial conifer forests dominate within a matrix of ecological and physical diversities. Checkerboard ownerships of private and public lands challenge landscape-wide management, and active special-interest groups and other public involvement often exert strong influence in management direction through engagement in regulatory processes (e.g., NEPA review of TNF plans and project proposals).

The SAP 4.4 case study identified that ecosystem management remained an effective management framework through which the TNF could address climate concerns. In confronting multiple ecological stressors such as fire, invasive species, insect and pathogen issues, TNF staff were already accommodating climate change impacts. Drought effects, amplified by 20th-century trends of rising temperatures, interacted with dense forest stands to create, for example, severe fire hazards, extreme flood events, and new opportunities for spread of invasive species. In the case of increasing fire hazards, such conditions resulted in anomalously severe wildfires on the TNF, which in turn provoked severe watershed erosion. TNF projects directed to alleviate these conditions were successful when implementation was possible, such as fuel reduction projects and prescribed burning. In other project treatments, such as salvage logging, herbicide applications, and post-fire watershed control of invasive species, there were often contentious challenges from opposing public opinions, which sometimes resulted in loss of opportunity to implement treatments.

TNF staff recognized further options to improve adaptation to climate such as: maintaining year-round fire staff to combat off-season wildfires, considering alternative species mixes and germplasm choice for reforestation, and prioritizing sensitive-species management actions at the 'leading edge' of species ranges (likely favorable future habitats) rather than 'trailing edges'. The potential for climate change impacts drove decisions about how to set priorities in project implementation on the TNF. In some cases planned projects, such as meadow restoration where retention of meadows in the future seemed unlikely, were put at low priority or re-evaluation for whether to proceed at all. Future needs identified on the TNF for incorporating climate included providing educational opportunities for national forest staff and public groups on climate topics, developing a rapid assessment method to evaluate new projects for climate robustness, utilizing ecosystem services frameworks and markets as priority-setting tools, and managing at whole watershed scales. Diverse climate tools requested by TNF staff included quantitative models about future climates and ecosystem responses, scenario-based exercises and visualization tools that aid understanding of potential futures, fire- and fuel-projection models, and priority-setting tools. On the TNF, the following general principles were recognized as opportunities for adaptation: (1) managing for drought- and heat-tolerant species and ecotypes, (2) reducing the impact of current anthropogenic stressors, (3) managing for diverse successional stages, (4) spreading risks by including buffers and redundancies in natural environments and plantations, and (5) increasing collaboration with interested stakeholders.

4. Conclusion

While we have suggested practical tactics, we emphasize that general solutions at the ground level, the resource managers' domain, do not yet fully exist. They will be wrought from collaborative discussion among colleagues—scientists, resource managers, planners, and the public—and they will be case-, location-, and project-specific. While general principles will emerge, the best preparation is for managers and planners to remain informed about the emerging climate, vegetation, and fire science in their region and to use that knowledge to shape effective local solutions. This work emphasizes the impacts of fire in Mediterranean forests, in other forested regions in the world where insects, disease, or wind-throw are the primary disturbance agents, a different set of management tools may need to be developed.

For forests that have been significantly disturbed and are far outside historical ranges of variation, restoration treatments are often prescribed (Moore *et al* 1999). Realignment or entrainment with future conditions rather than restoration to historical pre-disturbance conditions may be a preferred choice. In this case, management seeks to bring processes of the disturbed landscape into the range of current or expected future environments (Halpin 1997). However, restoration of forests to their pre-historic structure would result in forests that are more resilient and resistant to expected changes in climate and disturbance regimes when compared to the vast majority of current forests in the US.

Changing climates have and will continue to occur in western North America. What is novel in the current condition are two situations (1) high and increasing carbon dioxide concentrations in the atmosphere, which are unprecedented in the past 24 million years (Pearson and Palmer 1990), and (2) by far most important, the pervasive human footprint extensively and intensively across the landscape. The latter precludes the capacity of biota to respond as they would have under pre-modern-societal conditions; the natural mechanisms of coping with climate variability and disturbance are limited because of the human footprint.

We believe that managing for species persistence at the broad ecoregion scale is an appropriate goal when considering the effects of changing climates in this century. Such a goal relaxes expectations that current species ranges will remain constant, or that population abundances, distribution, species compositions, and dominances should remain stable. Management practices such as assisting species migrations, creating porous landscapes (managed matrix landscapes providing habitat through which target species can move), or increasing diversity in genetic and species planting mixes may be appropriate. Allowing fundamental ecosystem processes to operate within landscapes is critical. Essential to managing for uncertainty is the use of adaptive management to learn from past experiences. Strong adaptive management programs will be essential to any strategy that seeks to inform and make the best decisions in a changing climate. Management and political institutions will need to acknowledge and embrace uncertainty in the future since we are moving into an era with few analogs and inevitably, there will be surprises.

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