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CLIMATE CHANGE AND FORESTS OF THE FUTURE: MANAGING IN THE FACE OF UNCERTAINTY

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Abstract. We offer a conceptual framework for managing forested ecosystems under an assumption that future environments will be different from present but that we cannot be certain about the specifics of change. We encourage flexible approaches that promote reversible and incremental steps, and that favor ongoing learning and capacity to modify direction as situations change. We suggest that no single solution fits all future challenges, especially in the context of changing climates, and that the best strategy is to mix different approaches for different situations. Resources managers will be challenged to integrate adaptation strategies (actions that help ecosystems accommodate changes adaptively) and mitigation strategies (actions that enable ecosystems to reduce anthropogenic influences on global climate) into overall plans. 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), and *response* options (facilitate transition of ecosystems from current to new conditions). Mitigation strategies include options to sequester carbon and reduce overall greenhouse gas emissions. Priority-setting approaches (e.g., triage), appropriate for rapidly changing conditions and for situations where needs are greater than available capacity to respond, will become increasingly important in the future.

Key words: carbon sequestration; climate change; desired conditions; ecosystem management; facilitated conservation; forest management; historical variability; resilience; resistance; wildfire.

Introduction

During the last several decades, forest managers have relied on paradigms of ecological sustainability, historical variability, and ecological integrity to set goals and inform management decisions (Lackey 1995, Landres et al. 1999). These concepts commonly use historical forest conditions, usually defined as those that occurred before Euro-Americans dominated North American landscapes, as a means of gaining information about how healthy forests should be structured. There is no doubt that historical data have immense value in improving our understanding of ecosystem responses to environmental changes and setting management goals (e.g., Swetnam et al. 1999). However, many forest managers also use the range of historical ecosystem conditions as a management target, assuming that by restoring and maintaining historical conditions they are maximizing chances of maintaining ecosystems (their goods, services, amenity values, and biodiversity) sustainably into the future. This approach is often taken even as ongoing climate changes push global and regional climates beyond the bounds of the last several centuries to millenia (Intergovernmental Panel on Climate Change 2007). As importantly, novel anthropogenic stressors such as pollution, habitat fragmentation, land-use changes, invasive plants, animals, and pathogens, and altered fire regimes interact with climate change at local to global scales. The earth has entered an era of rapid environmental changes that has resulted in conditions without precedent in the past no matter how distantly we look. Attempts to maintain or restore past conditions require increasingly greater inputs of energy from managers and could create forests that are ill adapted to current conditions and more susceptible to undesirable changes. Accepting that the future will be different from both the past and the present forces us to manage forests in new ways. Further, although quantitative models can estimate a range of potential directions and magnitudes of environmental changes and forest responses in the future, models rarely can predict the future with the level of accuracy and precision needed by resource managers (Pilkey and Pilkey-Jarvis 2007). We might feel confident of broad-scale future environmental changes (such as global mean temperature increases), but we cannot routinely predict even the direction of change at local and regional scales (such as increasing or decreasing precipitation). A healthy skepticism leads us to use models to help organize our thinking, game different scenarios, and gain qualitative insight on the

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range of magnitudes and direction of possible future changes without committing to them as forecasts.

Facing an unknowable and uncertain future, however, does not mean "anything goes" for natural resource management. Managing in the face of uncertainty will require a portfolio of approaches, including short-term and long-term strategies, that focus on enhancing ecosystem resistance and resilience as well as assisting forested ecosystems to adapt to the inevitable changes as climates and environments continue to shift. Historical ecology becomes ever more important for informing us about environmental dynamics and ecosystem response to change. We offer here a conceptual framework for developing forest management strategies in a context of change.

Forest and Ecosystem Management in the Face of Change

The premise of an uncertain but certainly variable future is effectively best addressed with approaches that embrace strategic flexibility, characterized by risk-taking (including decisions of no action), capacity to reassess conditions frequently, and willingness to change course as conditions change (Hobbs et al. 2006). Learning from experience and iteratively incorporating lessons into future plans (adaptive management in its broadest sense) is the necessary lens through which natural resource management must be conducted (Spittlehouse and Stewart 2003, Stephens and Ruth 2005). Decisions that emphasize ecological process, rather than structure and composition, become critical (Harris et al. 2006). An example is increased use of managed wildfire in remote places (Collins and Stephens 2007). Similarly, institutional flexibility will be more effective than rigid or highly structured decision making.

A central dictum under uncertain futures is that no single approach will fit all situations (Spittlehouse and Stewart 2003, Hobbs et al. 2006). A toolbox approach, from which various treatments and practices can be selected and combined to fit unique situations, will be most useful. Some applications will involve traditional management approaches, but used in new locations, seasons, or contexts. Other options may require experimenting with new practices. A toolbox approach recognizes that strategies may vary based on the spatial and temporal scales of decision-making. Planning at regional scales will often involve acceptance of different levels of uncertainty and risk than appropriate at local scales (Saxon et al. 2005).

The framework of options presented below includes both adaptation strategies, that is, actions that help forested ecosystems accommodate changes, and mitigation strategies, actions that reduce the causes of stress, such as reducing anthropogenic climate change by sequestering CO_2 and reducing greenhouse gases (Papadopol 2000, Millar et al. 2006). Integrative approaches that combine adaptation and mitigation practices in complementary ways are favored. A first consideration in building an integrative strategy is to evaluate the types of uncertainty. These could include, for example, knowledge about present environmental and ecological conditions, models and information sources about the future, institutional resources (staff, time, funds available), planning horizon (short- vs. long-term), and public and societal support (Lindner et al. 2000, Wheaton 2001). A further decision is whether, or to what degree, to adopt deterministic or indeterministic approaches. The former accepts certain kinds of information about the future as reliable enough upon which to base decisions. By contrast, indeterministic approaches base planning on an assumption that information about the future is not adequately known, and plan instead directly for uncertainty. Deterministic approaches "put all the eggs in one basket" and risk potential failures if an assumed future does not unfold, whereas indeterministic approaches employ "bet hedging" strategies that attempt to minimize risks by taking multiple courses of action. Below we offer management options and examples for populating a manager's climate-change toolbox.

Adaptation Options

Create resistance to change

One set of adaptive options 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). Whereas this may seem a denial of future change, it is a defensible approach to uncertainty. From high-value plantations near harvest to high-priority endangered species with limited available habitat, maintaining the status quo for a short time may be the only or best option. Resistance practices seek to improve forest defenses against direct and indirect effects of rapid environmental changes. In western North America these will commonly include reducing undesirable or extreme effects of fires, insects, and diseases (Agee and Skinner 2005). Treatments might include complete fuel breaks around highest risk or highest value areas (such as wildland–urban interfaces, forests with high amenity or commodity values, or at-risk species); intensive removal of invasives; or interventions such as those used in high-value agricultural situations (resistance breeding, novel pheromone applications, or herbicide treatments). Abrupt invasions, changes in population dynamics, and long-distance movements of native and nonnative species are expected in response to changing climates (Keeley 2006). Climate changes may also catalyze conversion of native insects or disease species into invasive species in new environments, such as with mountain pine beetle (*Dendroctonus ponderosae*) east of the Continental Divide in Canada (Carroll et al. 2006). Taking early defensive actions at key migration points to remove and block invasions is important to increase resistance.

Resisting climatic and other environmental changes to forests often may require intensive intervention, accelerating efforts and investments over time, and a recognition that eventually these efforts may fail as conditions change cumulatively. Creating resistance to directional change is akin to "paddling upstream," and eventually conditions may change so much that resistance is no longer possible. For instance, site capacities may shift from favoring one species to another. Forests that have been treated to resist climate-related changes may cross thresholds and be lost catastrophically (Harris et al. 2006). For this reason, resistance options are best applied in the short-term and to forests of high value. Forests with low sensitivity to climate may be those most likely to accommodate resistance treatments, and high-sensitivity forests may require the most intensive efforts to maintain.

Promote resilience to change

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 (Dale et al. 2001, Price and Neville 2003, Spittlehouse and Stewart 2003), but like resistance, is not a panacea. Resilience in forest ecosystems can be increased through practices similar to those described for resisting change but applied more broadly, and specifically aimed at coping with disturbance (Dale et al. 2001, Wheaton 2001). Given that the plant establishment phases tend to be most sensitive to climate-induced changes in site potential (Betancourt et al. 2004), surplus seed-banking (Ledig and Kitzmiller 1992), and intensive management during revegetation through early years of establishment may enable retention of desired species, even if the site is no longer optimal (Dale et al. 2001, Spittlehouse and Stewart 2003).

Capacity to maintain and improve resilience may become more difficult and require more intensive intervention as changes in climate accumulate over time. These options are best exercised in projects that are short-term, have high amenity or commodity values, or under ecosystem conditions that are relatively insensitive to climate change effects.

Enable forests to respond to change

This group of adaptation options intentionally accommodates change rather than resists it, with a goal of enabling or facilitating forest ecosystems to respond adaptively as environmental changes accrue. Treatments implemented would mimic, 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. The strategic goal is to encourage gradual adaptation and transition to inevitable change, and thereby to avoid rapid threshold or catastrophic conversion that may occur otherwise.

Depending on the context, management goals, and availability and adequacy of modeling information (climate and otherwise), different approaches may be chosen. Changes in fundamental ecosystem state are assumed to happen, either in some general direction (deterministic) where specific goals are planned for the future, or in unknown directions (indeterministic) where goals are developed for uncertainty. A sample of potential practices follows.

1. *Assist transitions, population adjustments, range shifts, and other natural adaptations*.—Qualitative indications of future change may be adequate to trigger actions at least in broad outline. With such information, managers might plan for transitions to new conditions and habitats, and assist the transition, e.g., as appropriate, assist species migrations along expected climatic gradients, plan for higher-elevation insect and disease outbreaks, anticipate forest mortality events and altered fire regimes, or accommodate loss of species' populations on warm range margins (Ledig and Kitzmiller 1992, Parker et al. 2000). For forest plantations, examples would include modifying harvest schedules, altering thinning prescriptions and other silvicultural treatments, replanting with different species, shifting desired species to new plantation or forest locations, and taking precautions to mitigate likely increases in stress on plantation and forest trees.

A nascent literature explores the advantages and disadvantages of "assisted migration," that is, intentional movement of propagules or juvenile and adult individuals into areas assumed to be their future habitats (Halpin 1997, McLachlan et al. 2007). Some environments have broad and regular gradients, making adaptive migration directions obvious. Others, such as patchy mountainous terrain, are heterogeneous, and migration direction is far more difficult to determine. On-the-ground monitoring of native species can provide insight into what organisms are experiencing, and indicate the directions of change and appropriate response at local scales. This can allow management strategies to mimic emerging natural adaptive responses rather than rely on quantitative projections. For instance, new species mixes (mimicking what is regenerating naturally or outperforming plantation species), altered genotype selections, modified age structures, and new management contexts (e.g., uneven vs. even-aged management, altered prescribed fire regimes) may be considered.

2. *Increase redundancy and buffers*.—Here we suggest using redundancy and creating diversity through practices that spread risks rather than concentrate them. These can be achieved, for instance, by introducing species over a range of environments rather than within historical distribution, "preferred habitat," or projected future environments. Redundant plantings across a range of environments can provide monitoring infor-

mation if survival and performance are measured and analyzed. Reexamining replicated forest plantations, such old genetic provenance or progeny tests, is a means of gathering information about adaptation to recent and ongoing changes. Opportunistic assessment, such as of horticultural plantings of native species in landscaping, gardens, roadsides, or parks, can give clues on how species respond in different locations as climate changes.

3. *Expand genetic diversity guidelines*.—Existing guidelines for genetic management of forests and restoration projects specify actions to retain local gene pools. In the past, strict transfer rules that minimized movement of germplasm and small seed zones were developed to avoid contamination of populations with ill-adapted genotypes. These rules were based on assumptions that neither environments nor climate were changing. Relaxing these guidelines may be appropriate under assumptions of changing climates (Ledig and Kitzmiller 1992, Spittlehouse and Stewart 2003, Millar and Brubaker 2006). In this case, either deterministic or indeterministic options could be chosen. In the former, germplasm would be moved in the expected adaptive direction, for instance, rather than using local seed, seed from a warmer population would be used. New transfer rules could be developed for expected future climate gradients. By contrast, if an uncertain future is assumed, expanding seed zone sizes or relaxing rules to admix germplasm from adjacent zones might be considered. Adaptive management of this nature is experimental by design, should be undertaken cautiously, and requires careful documentation of treatments, seed sources, and outplanting locations to learn from both failures and successes.

Enforcing traditional best genetic management practices that equalize germplasm contributions and enhance effective population sizes becomes especially important under uncertain futures. Genotypes known or selected for broad adaptations would also be favored. By contrast, using a single or few genotypes (e.g., a select clone or small clonal mix) is far riskier in a long-term context of uncertainty.

4. *Manage for asynchrony and use establishment phase to reset succession*.—Changing climates over paleohistorical time scales have repeatedly altered biotic communities as plants and animals responded to natural changes (Huntley and Webb 1988). To the extent that climate acts as a region- and hemispheric-wide driver of change, the resulting shifts in biota often occur as synchronous changes across the landscape (Betancourt et al. 2004). At decadal and centennial scales, for instance, recurring droughts in the west and windstorms in the east have synchronized forest composition and age- and stand structure across broad landscapes, which then become vulnerable to climate shifts. This appears to have happened in some western forests as widespread drought has induced diebacks (Breshears et al. 2005). Opportunities exist to manage early successional stages following widespread mortality by deliberately reducing landscape synchrony (Betancourt et al. 2004). Asynchrony can be achieved by promoting diverse age classes, species mixes, within-stand and across-landscape structural diversities, and genetic diversity. Early successional stages provide the most practical opportunities for resetting ecological trajectories in ways that are adaptive to present and future rather than past conditions.

5. *Establish "neo-native" forests*.—Information from historical species ranges and responses to climate change can provide unique insight about species responses, ecological tolerances, and potential new habitats. Areas that supported species in the past under similar conditions to those projected for the future might be considered sites for "neo-native" stands of the species. These may even be outside the current species range, in locations where the species would otherwise be considered exotic. For instance, Monterey pine (*Pinus radiata*), endangered throughout its small native range, has naturalized along the north coast of California distant from its present native distribution. Much of this area was paleohistorical range for the pine, extant during climate conditions that have been interpreted to be similar to expected futures in California. Using these locations for "neo-native" conservation stands, rather than removing trees as undesired invasives, is an example of how management could accommodate climate change (Millar 1998).

6. *Promote connected landscapes*.—The capacity to move (migrate) in response to changing climates has been key to adaptation and long-term survival of plants and animals in historical ecosystems. Plants migrate (shift ranges) by dying in unfavorable sites and colonizing favorable sites, including internal species' margins. The capacity to do this is aided by managing for connected landscapes, that is, landscapes that contain continuous habitat with few physical or biotic impediments to migration, and through which species can move readily (Halpin 1997, Noss 2001). Promoting connected forested landscapes with flexible management goals that can be modified as conditions change may assist species to respond naturally to changing climates (Noss 2001). Desired goals include reducing fragmentation and planning at large landscape scales to maximize habitat connectivity.

7. *Realign significantly disrupted conditions*.—For forests that have been significantly disturbed and are far outside historical ranges of variation, restoration treatments are often prescribed. Re-alignment or entrainment with current and expected future conditions rather than restoration to historical pre-disturbance conditions may be a preferred choice (Harris et al. 2006, Millar and Brubaker 2006). In this case, management seeks to bring processes of the disturbed landscape into the range of current or expected future environments (Halpin 1997). The Mono Basin case in California exemplifies this approach, where water balance models were used to determine appropriate lake levels buffered

for current and expected future climate variability (Millar and Woolfenden 1999).

8. *Anticipate surprises and threshold effects.*—Evidence is accumulating that species interactions and competitive responses under changing climates can be complex and unexpected (Suttle et al. 2007). Managers can evaluate the potential for indirect and surprise effects that may result from cumulative climate changes or changes in extreme weather events. This involves anticipating events outside the range of conditions that have occurred in recent history. For example, reductions in mountain snowpacks lead to more bare ground in spring such that even "average" rain events may run off immediately, rather than being buffered by snowpacks, and produce extreme unseasonal floods. In many parts of western North America, additional stresses of extended summer water deficits are pushing plant populations over thresholds of mortality, as occurred in the recent multi-year droughts in the Southwest (Breshears et al. 2005). Other examples already observed in some areas are year-round fire seasons and fires in atypical locations, such as subalpine and coastal environments.

9. *Experiment with refugia.*—Plant ecologists and paleoecologists recognize that some environments are more buffered against climate change and short-term disturbances than others. If such environments can be identified, they could be considered sites for long-term retention of plants or for establishment of new forests. For instance, microclimates in mountainous regions are highly heterogeneous. Furthermore, unusual and nutritionally extreme soil types (e.g., acid podsol, ultramafic, limestone) have been noted for their long persistence of species and genetic diversity, resistance to invasive species, and long-lasting community physiognomy compared to adjacent fertile soils. During historical periods of rapid climate change and widespread population extirpation, refugial populations have persisted on unusual local sites that avoided extremes of regional climate impacts or the effects of large disturbance (Huntley and Webb 1988).

Mitigation Options

Reduce greenhouse gases

This set of options has the goal of using forested environments to ameliorate greenhouse gas emissions and sequester carbon, thereby lessening the human impact on climate. The forestry sector has a huge potential to contribute at global to regional scales (Malhi et al. 2002). Evaluating and determining best choices, however, are hampered by considerable uncertainty and difficulty in analyzing net carbon balances (Cathcart and Delaney 2006).

1. *Sequester carbon.*—Forest management strategies designed to achieve goals of removing CO_2 and storing carbon are diverse, and include avoiding deforestation, promoting afforestation and reforestation, manipulating vegetation to favor rapid growth and long-term site retention, and sequestering carbon after harvest in wood products (Harmon and Marks 2002, Kobziar and Stephens 2006, Krankina and Harmon 2006). Some approaches duplicate long-recognized best forest-management practices, where goals are to maintain healthy vigorous trees, keep sites fully occupied with minimal spatial or temporal gaps in non-forest conditions, and minimize severe disturbance by fire, insects, and disease. As noted above, however, in many cases uniform forest conditions are best avoided, as they are vulnerable to mortality from insects, disease, and fire (Stephens and Moghaddas 2005*a*, Stephens et al. 2007). Under changing climates, these conditions may need to be intensively managed to minimize risk of severe fire (Weatherspoon and Skinner 1995), and to reduce the potential for carbon losses from wildfire.

Once wood is removed from the forest or plantation, its subsequent use affects its sequestration status. Options for minimizing return of carbon to the atmosphere include storing carbon in wood products, or using it as biomass to fuel electricity production, thereby providing alternative forms of energy to replace fossil fuels. For successful choices to be made, life-cycle analysis research must assess carbon accounting from forest through utilization phases (Cathcart and Delaney 2006).

2. *Reduce emissions.*—Wildfire and extensive forest mortality as a result of insect and disease are primary sources of unintentional carbon emissions from forests in western United States (Stephens 2005), and can lead to widespread loss of centuries' worth of carbon storage. This effect will likely be exacerbated in coming decades under continued warming, with increasingly severe fire years leading to what have been modeled as widespread "brown-downs" for many western and eastern forest types (Westerling et al. 2006).

One obvious means of slowing this release of sequestered carbon is to increase forest resistance to fire, drought, and disease, usually by reducing the density of small trees. In roaded or otherwise accessible areas, such density reductions might be accomplished by mechanical thinning, prescribed fires, or both (Stephens and Moghaddas 2005*b*). In remote or rugged terrain, wildland fire use or appropriate management response suppression fire may be the only reasonable option (Collins et al. 2007). In either case, some carbon inevitably will be released in the process of increasing forest resistance to sudden release of much greater quantities of carbon. If small trees are physically removed during the density reduction, then subsequently used for energy generation or long-term sequestration, the net carbon release might be minimized.

Prioritizing Management Under Conditions of Rapid Change

Species respond to changing climates and environments individualistically. Some species will be sensitive and vulnerable whereas others will be naturally buffered and resilient to climate-influenced disturbances. Management goals across the spectrum of forest types and ownerships also vary. As a result, proactive climate planning will include a range of approaches having different management intensities. Some species and ecosystems may require aggressive treatment to maintain viability or resilience, others may require reduction of current stressors, and others less intensive management, at least in the near future.

Evaluating priorities has always been important in resource management. However, the magnitude and rate of change and the management responses these demand, combined with finite human resources and declining budgets, dictate that priorities be evaluated swiftly and definitively. A useful systematic approach for prioritizing high-demand situations might be adopted from the medical practice of triage (Fitzgerald 2000). Deriving from the French word *triare*, to sort, triage approaches were developed from the need to prioritize care of injured soldiers in battlefield settings where time is short, needs are great, and capacity to respond is limited. Triage applied in a resource context offers a systematic process to sort management situations into categories according to urgency, sensitivity, and capacity of available resources to achieve desired goals. Cases are rapidly assessed and divided into three to five major categories that determine treatment priority. The categories range from high urgency (treat immediately), mid-urgency (treat later), to highly urgent but untreatable given current capacity (no action taken). Reassessing and re-prioritizing must be done frequently, especially when conditions are changing rapidly.

Although triage approaches are valuable under conditions of scarce resources or overwhelming choice, they are rarely adequate as long-term approaches. Other planning processes may be used for prioritizing current management plans and practices. An example is rapid assessments of forest management plans by teams of climate-expert reviewers who convene to intensively review existing management plans, assess current needs, and recommend top priorities for revision.

Conclusions

Over the last several decades, forest managers in North America have used concepts of historical range of variability, natural range of variability, and ecological sustainability to set goals and inform management decisions. An underlying premise in these approaches is that by maintaining forest conditions within the range of presettlement conditions, managers are most likely to sustainably maintain forests into the future. We argue that although we have important lessons to learn from the past, we cannot rely on past forest conditions to provide us with adequate targets for current and future management. This reality must be considered in policy, planning, and management. Climate variability, both naturally caused and anthropogenic, as well as modern land-use practices and stressors, create novel environmental conditions never before experienced by ecosystems. Under such conditions, historical ecology suggests that we manage for species persistence within large ecoregions. 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, or increasing diversity in genetic and species planting mixes may be appropriate. Essential to managing for uncertainty is the imperative to learn-as-you-go. Although general principles will emerge, the best preparation is for managers and planners to remain informed both about emerging climate science as well as land-use changes in their region, and to use that knowledge to shape effective local solutions. A goal of this paper is to engage dialogue on this issue.

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