Silviculture and Forest Management Under a Rapidly Changing Climate[1]

Carl N. Skinner[2]

Abstract

Climate determines where and how forests grow. Particularly in the West, precipitation patterns regulate forest growth rates. Wet years promote "boom" vegetative conditions, while drought years promote "bust." Are managers safe in assuming that tomorrow's climate will mimic that of the last several decades? For the last ~100 to ~150 years, climate has been warming at what appears to be an unusually rapid rate and is projected to continue into the foreseeable future. Increased temperatures are projected to lead to broad-scale alteration of storm tracks changing precipitation patterns in both seasonality and amounts. Multiple lines of paleoecological data show that such changes in the past, which were rarely as rapid, were accompanied by major reorganization of vegetation at continental scales. Exercises in modeling of possible ecological responses have shown the complexity in understanding potential responses of forests. Additionally, these exercises indicate that dramatic changes in natural disturbance processes are likely. Indeed, some believe that the responses of disturbance regimes to climate change may be emerging in the more frequent outbreaks of very large fires, widespread tree die-off across the southwest, expansive insect infestations in the Rocky Mountains, and more rapid and earlier melting of snow packs through the West. Developing both short- and long-term forest management responses will be challenging. Therefore, silviculturists must be aware of the nature of and implications of climate change in order to develop management strategies that may help to reduce adverse effects while sustaining healthy, productive forests.

Introduction

The successful practice of silviculture depends on a strong understanding of the relationships of species to climate in order to manage forests to meet many of society's needs from wood products to wildlife habitat. Climate is a great controller of our environment. Climate determines where and how forests grow. The type of climate for any particular place is a consequence of long-term, generalized weather conditions over gradients of time from days to seasons to decades or centuries. Climate includes not only the central tendencies or 'average' weather, but also the patterns of variation and nature of the extremes. Each species has a more or less unique geographical distribution that is related to its particular range of adaptations to climate and other environmental factors. Thus, climate strongly determines the potential for a species to grow and thrive in any particular place.

Some controversy surrounds the causes of the current climate change, but the evidence that climate is changing is compelling (Parmesan and Yohe 2003,

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[2] Geographer and Science Team Leader, Pacific Southwest Research Station, USDA Forest Service, Silviculture Laboratory, 3644 Avtech Parkway, Redding, CA 96002.

Appenzeller and Dimick 2004). It is not the intent of this paper to spend time on the possible causes or 'blame' for the current rapid climate change. To do so often diverts attention from the more immediately important discussion of how climate change will likely affect the ability to be successful forest managers. Indeed, the relative contributions of natural climatic variation and human-induced climate change will likely not be known for decades (Hughes 2000). Rather, the objectives in writing this paper are to (1) describe the evidence indicating that climate is changing rapidly, and (2) discuss the implications of climate change for forest managers.

Climate Change

We know that climate has undergone large fluctuations in the past, oscillating between cold ice ages and warm temperate periods over many 1000s of years. The common view has been that climatic variations take place over long time scales and, though intellectually interesting, are not relevant to practical forest management. Thus, day-to-day forest management has largely been conducted from a perspective that climate is relatively stable over relevant time scales and what were successful practices over the last several decades will likely continue to be successful into the foreseeable future. However, in light of recent research on climate variation, continuing to manage from this perspective may leave one quite vulnerable to undesirable consequences.

Multiple lines of evidence developed in the late 20th Century are providing more complete descriptions of past climatic variation, the characteristics of past climate changes, and associated ecological responses. Since the instrumental record is so short (little more than a century in many parts of the country), the development of this evidence has relied on interpretations and inferences drawn from proxy or indirect records of climate. Proxy records used for reconstructing descriptions of past climate variation come from ice cores, sediment cores, packrat middens, corals, and tree-rings among others (Stokstand 2001).

Each proxy has different potentials for temporal depth and resolution. Sediment cores may include from several thousand to millions of years of pollen, charcoal, and other biological indicators (Davis 2001, Whitlock and Anderson 2003). Packrat middens may include up to ~40,000 years of information (Rhode 2001). Both methods are usually limited to 50+ years of resolution, although sediment cores occasionally may be found that are annually laminated. Ice cores provide seasonal to decadal resolution for up to 40,000 years, while annual resolution is provided by corals for up to 400 years and tree rings for up to several thousand years (Stokstad 2001).

Though each proxy has its pluses and minuses, together they provide complimentary information that allows us to gain a more comprehensive understanding of the temporal and spatial scales of climatic variability. The picture that emerges indicates climate is continually changing at varying rates due to multiple, nested scales of oscillations responding to a variety of climate forcing factors (Millar 2005). Abrupt shifts (major changes on a decadal scale or less) in climate have been found to be associated with periods of rapid, low-frequency climate change similar to what we are currently experiencing. This potential for abrupt change is thought to be due to response to the achievement of particular threshold conditions (NRC 2002). Notably, the current period is one of exceptionally rapid warming (Stanley 2000).

Temperature

The warming of the 20th Century that continues to today reversed a millennial-scale cooling trend (Mann et al. 1999). The rapidity of changing conditions is exemplified by the switch from the 1800s as the second coldest century to the 1900s being the warmest century (1900s) of the last millennium with much of the warming taking place from 1920-1945 and 1975 to the present (Jones et al. 2001).

Though the Earth's average atmospheric temperature has warmed considerably over the last century, the warming has not been temporally or spatially uniform. For the Northern Hemisphere, more pronounced increases have taken place through the raising of diurnal minimum, winter, high latitude, and high altitude temperatures than diurnal maximum, summer, low latitude, and low altitude temperatures (Jones et al. 2001, Walther et al. 2002). Average nighttime and winter temperatures have increased at twice the rate of daytime (Walther et al. 2002) and summer temperatures (Jones et al. 2001). Modeling exercises project that atmospheric temperatures across the continental United States are likely to continue to increase to between approximately 2^{O}C (3.6^{O}F) and 6.6^{O}C (11.9^{O}F) by the end of the 21st Century (Hansen et al. 2001).

Water

The influence of climate on vegetation is primarily manifested through the interactions of energy input (temperature) and the water available for plant growth and decomposition (Olsen 1969, Stephenson 1990). Most models predict increases in average global precipitation will accompany increasing temperature. The average annual precipitation has increased over the 20th Century across the United States (Hughes 2000). However, the regional distribution will vary from wetter in some areas to dryer in others with additional changes seen in seasonality and type of precipitation (Hughes 2000, Mote et al. 2003). For example, there has been a 10% reduction in annual snow and ice cover of the earth since the 1960s (Walther et al. 2002). Thus, the actual water available for tree growth may increase or decline depending upon how the interaction of temperature and moisture are manifested regionally and locally (Walther et al. 2002, Mote et al. 2003).

Climate change is expected to alter the energy/water balance influencing plant growth, disturbance processes, and patterns of habitat. In western North America, several important hydrologic patterns have emerged over the closing decades of the 20th Century – an earlier onset of spring peak stream flows, a shortened annual period of warm-season snow packs due to earlier and more rapid snowmelt (Cayan et al. 2001, Mote et al. 2003, Stewart et al. 2004), and greater interannual variation in stream flow (Jain et al. 2005). A consequence of these changes is a greater proportion of stream flows in winter-spring with lower flows in summer (Regonda et al. 2005). As the effects of evapotranspiration instead of snowmelt come to dominate many streams, they will change their diurnal peak flows to early morning from late afternoon (Lindquist and Cayan 2002). In terms of available soil moisture, the earlier onset to spring drying and earlier snowmelt reduces available soil moisture over the course of the warmer growing season potentially creating greater stress for vegetation (Stephenson 1998).

Potential Ecosystem Responses to Global Warming

Climate influences where and how forests grow through spatiotemporal variation in environmental factors that include atmospheric temperature, precipitation, wind, and humidity. Global temperature has been increasing rapidly along with atmospheric concentrations of CO_2 over the last several decades and is expected to continue through this century. These changes in temperature are expected to be associated with changes in spatiotemporal patterns of precipitation and water availability (Mote et al. 2003, Stewart et al. 2004) which in turn are expected to affect patterns of disturbances and other agents of change (Ayres and Lombardero 2000, Logan and Powell in review), all of which combine to affect where and how species of trees are able to grow (Davis and Shaw 2001, Iverson and Prasad 2002, Hughes 2000, Shafer et al. 2001).

Silvicultural strategies will benefit from an understanding of processes and likely biophysical responses to climate change that cascade ecosystems through effects on physiology, phenology, range and distribution, and abundance of species (Harrington et al. 2001, Walther et al. 2002). Though the response of ecosystems to projected changes is likely to be quite complex (Neilson and Drapek 1998, Walther et al. 2002), there are some key variables that will be particularly of interest to forest managers.

Disturbance

A warming climate is likely to increase the occurrence of extremes for many types of disturbance processes – wind, floods, drought, insects, pathogens, and fires. Each of these disturbance processes will affect our ability to manage forests for desired outcomes. This paper focuses on drought, insects, and fire, since they are more likely to affect broad, regional areas and their interactions have potential to significantly affect atmospheric carbon (Breshears and Allen 2002, Harrington et al. 2001).

Drought

North American droughts of the 20th Century, though known to have caused great economic hardship, were unusually benign and not representative of the full range of variability compared to multi-year droughts of the last millennium (Cook et al. 2004, Stine 1994, Woodhouse and Overpeck 1998). Regional drought may cause widespread changes to ecosystems both directly through mortality of susceptible species and indirectly by creating conditions that more readily support high intensity fires or insect outbreaks. Climate change modeling predicts that portions of the country, such as the Southwest, may experience more prolonged and severe droughts with continued warming.

The more severe effects of drought, especially under a rapidly changing climate, are apt to be realized along major ecotones where vegetation is normally under some stress. A severe drought in the 1950s in New Mexico provides an example of the potential influence of drought on forest species distributions along an ecotone boundary. The impact of this drought, enhanced by bark beetle activity in a landscape where vegetation had become increasingly dense over the early 20th Century, was sufficient to cause the ecotone between ponderosa pine forest and piñon-juniper woodland to shift up to 2 km as ponderosa pine retreated to higher elevation. Additionally, the shift of this ecotone boundary has persisted for over 40 yrs (Allen and Breshears 1998).

The direct effects of drought are usually seen in reduction of tree growth, but direct mortality may occur in more extreme situations (Guarín and Taylor 2005). More commonly, significant changes in stand conditions and mortality occur indirectly from other agents such as insects or fire that are facilitated by the dry conditions. Whether drought induced ecological changes become a more permanent condition will depend on the severity of the effects and the response of the ecosystem to the future climate trajectory.

Insects

Climate change is expected to alter host / insect relationships through effects on physiology, phenology, and species distributions (Hughes 2000, Harrington et al. 2001, Williams and Liebohold 2002). Though, resulting manifestations of these effects will likely be complex and not necessarily predictable, Harrington et al. (2001) summarize some of the more general potential effects:

- ***Physiology*** Warming temperatures, especially in regions where insects have been limited by severe cold, will allow some species to survive in regions that were previously unfavorable. Additionally, the longer annual warm periods will allow some species to produce more broods.

- ***Phenology*** For species whose life-cycle events are controlled by temperature, warming temperatures will likely lead to changes in timing of flowering and growth in trees as well as in activity in insect populations. Where species with life cycles controlled by photoperiod interact with species controlled by temperature, novel relationships are likely to develop.

- ***Distributions*** Altered distributions of both potential hosts and insect species are likely to be a result of the effects of climate change on physiology and phenology. These potential changes are expected to bring into contact populations of trees and insects whose distributions did not previously overlap.

The recent expansion of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) into environments where it was previously limited by effects of extreme winter cold on broods (Carroll et al. 2004, Logan and Powell in review) may be one dramatic example of response to such alterations. In recent decades the mountain pine beetle has moved northward into areas of British Columbia with previously unsuitable climate (Carroll et al. 2004). The effect of this migration has been dramatic mortality in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) populations not previously exposed to the beetle (Carroll et al. 2004, Logan and Powell in review). It has been suggested that a continued warming of the climate could allow this insect species to migrate into jack pine (*P. banksiana* Lamb.) populations on the eastside of the Rocky Mountains, presenting an avenue that may possibly allow the mountain pine beetle to move east and then south as far as the southern pine forests of Texas (Logan and Powell in review).

Fire

The combined effects of droughts and insects may lead to a pulse of tree mortality that increases the potential for intense fires. There is a short-term and a long-term facet to the increase in potential fire intensity. In the short-term, as long as the dead foliage remains on the trees, there may be a dramatic increase in the potential for intense crown fires. Once the dead foliage drops, this danger may be considerably reduced for a few years. However, as the trees decay over the next decade or so following the pulse of mortality, they fall and can help create an accumulation of large, heavy fuels. These large fuels contribute to a longer-term potential for intense fires since they may take many years to decompose, especially in the dry environments of the West.

Even in the absence of increased mortality from either drought or insects, a warming climate will likely alter fire regimes in ways that will make it more difficult to manage forests influenced by many decades of fire suppression and other activities. It is widely recognized that western forests have changed dramatically over the last century or so due to fire suppression, logging, grazing, and other activities. Fuel profiles have changed with stands becoming generally denser and often accompanied by increases in both ladder and surface fuels (Agee and Skinner 2005).

Climate change influences fire regimes in complex ways due to differentials in responses to variation in temperature and precipitation regimes. Both tree-ring records and modeling indicate that the probability of having fires is primarily driven by temperature whereas, the extent and intensity of fires is driven more strongly by precipitation patterns (Chang 1999, Flannigan and Van Wagner 1991, Swetnam 1993). Warmer temperatures lead to an earlier onset and later end for the drying period, thus increasing the probability of a fire during the longer fire season. Precipitation influences the growth of vegetation (fuel). The more/less precipitation in the wet season, the more/less fuel will be produced. In the occasional dryer years during moist periods, fires are likely to burn more extensively and intensely due to greater fuel accumulations. Conversely, fuels are likely to accumulate more slowly during longer periods of consecutively dry years. Once the initial fuel loads grown during the moist periods are consumed, though fires are expected to become more frequent in dryer periods, they are likely to be less extensive and less intense due to the limits to growth of new fuels in extended dry periods.

Under a warming climate, the general outlook is to expect a greater number of fires with more escaping initial-attack suppression activity due to the longer fire seasons (Fried et al. 2004). The past century of altering stand structures and accumulating live and dead fuels increases the probability that many fires in the dryer areas of the West will be of higher intensity than would have been likely under a historical fire regime (Agee and Skinner 2005).

Vegetation

Of great interest to silviculturists is how vegetation is likely to respond to changing climate. Different species will respond to climate change in different ways making it difficult to generalize about expected responses. However, altered productivity and changes in species distributions are likely to be two basic responses (Aber et al. 2001). Productivity will be affected by changes in temperature, precipitation, effective moisture, and competition among other factors. As climates change, species will migrate into new locations, while sometimes disappearing altogether from locations in which environmental factors become too stressful (Hansen et al. 2001, Joyce and Hansen 2001).

Climate change is likely to alter our potential to manage woody vegetation by affecting physiology, phenology, and distributions in ways similar to those described for insects. Such practices as spacing in tree plantations rely on assumptions about moisture availability and competition (Joyce and Hansen 2001), while scheduling of harvests depends on assumptions about productivity. Climate change is likely to alter competitive interactions and thus affect tree growth and the ability to achieve productivity goals.

Physiology

Moisture stress, especially in dryer regions, would tend to increase with warming temperatures. However, the increases in atmospheric CO_2 over the last century and projected into the next will increase efficiency of moisture use and offset, at least for sometime, the effects of increasing temperature. Plants with cold period requirements may not be able to receive sufficient cold exposure (Hughes 2000).

Phenology

Earlier onset of flowering and growth appears to be a response to warming temperatures in many species of trees. As a result, new interspecific relationships are likely to develop where species with life cycles responding to temperature interact with species controlled by photoperiod (Hughes 2000). For the silviculturist, these changes in competitive interactions will likely lead to new challenges in managing competing vegetation.

Distributions

Altered species distributions will likely be a result of the effect of climate change on physiology and phenology. One of the important things that paleoecology teaches us is that species distributions will change in response to climate (Davis and Shaw 2001, Whitlock 1992). Additionally, dramatic changes in species distributions can take place over scales of but a few decades to a century during periods of rapid climate variation (Davis and Shaw 2001, Peteet 2000). Notably, species respond to climate individualistically and not as plant communities or associations. Thus, current assemblages are likely to dissolve and coalesce into novel associations as species ranges adjust to a changing climate (Davis 1986, Whitlock 1992).

In order to better understand the potential re-distribution of species in North America, several projects projecting potential range shifts in tree species based on simulation of species responses to environmental changes have been undertaken (Iverson and Prasad 2002, Shafer et al. 2001). These studies use various models projecting climatic conditions (e.g., temperature, precipitation, growing days, etc.) coupled with spatial representation of a number of environmental variables (e.g., elevation and soils). These conditions are then compared to those in which species are currently found to create a ‘climate space’ for each species. This climate space is then presented geographically to represent where species would be expected to find favorable growing conditions under future climate projections. Prasad and Iverson (1999-ongoing) project that some species in the eastern United States may see little change in overall distribution (e.g., white oak [*Quercus alba* L.], red maple [*Acer rubrum* L.), whereas, other species (e.g., aspen [*Populus tremuloides* Michx.], paper birch [*Betula papyrifera* Marsh.], sugar maple [*A. saccharum* Marsh.]) may retreat northward into Canada as suitable climate space is lost.

The many changes in species distributions that are projected will bring into contact populations of trees and shrubs whose distributions did not previously overlap, introducing new inter-specific competitive relationships.

Genetics

Rapid climate change over the next century will likely render many species and local varieties less genetically suited to the environments in which they are currently found (Davis and Shaw 2001, Peteet 2000). Regeneration difficulties may be the earliest noticeable sign of the effects of climate change. Established, mature trees are often able to withstand a wide range of environmental conditions and will be able to survive for many years with effects primarily appearing as altered levels of productivity. However, establishing regeneration after logging or large fires may become more difficult since seedlings are often more sensitive to environmental conditions than are mature trees. Managers may want to consider mixing in seedlings from neighboring seed zones that may be better suited to the new local environment (Ledig and Kitzmiller 1992).

A lot of work has gone into selecting and breeding trees that perform exceptionally well under specific environmental conditions. Rapid climate change may reduce the ability of many plantations of such trees to perform to expectations. Using trees that do generally well under a variety of conditions may be better strategy than those that do exceptional under a narrow range of conditions (Ledig and Kitzmiller 1992).

Habitat

Highly altered habitat conditions for many animal species are likely to be a result of the complex changes in vegetation distributions that are expected with changing climate. Thus, the changing geography of favorable habitat for many animal species is likely to also lead to animal migrations and altered geographic distributions (Burns et al. 2003).

Managers are often required to manage for favorable habitat conditions in support of species of concern. Some examples are the requirements for 'old-growth' conditions for the northern spotted owl (*Strix occidentalis caurina*) in the Pacific Northwest, California spotted owl (S. o. *occidentalis*) in the Californias, and the Mexican spotted owl (*S. o. lucida*) in the Southwest. Many of the dominant species of trees important in the structure of these habitats regenerated and grew under very different past climates (Sprugel 1991). However, the influence of a warming climate on the likelihood of fires (as discussed above) may make it more and more difficult to sustain appropriate habitat without greater attention to landscape pattern, geographical context, and the realities of climate.

Specific types of locations in landscapes such as more mesic north facing slopes and the lower slopes of canyons are more likely to sustain 'old-growth' over longer periods of time than the landscape as a whole (Taylor and Skinner 1998, Beaty and Taylor 2001, Taylor and Skinner 2003). Therefore, it may be possible to learn from the past to help design landscape strategies that reduce the potential for unusually severe fires while improving the probability of maintaining sufficient habitat across landscapes (Taylor and Skinner 1998, Weatherspoon and Skinner 1996).

Conclusion

Climate is continuously changing, with some periods exhibiting rather stable, slowly changing climate, and other periods displaying great variation with rapidly changing climate. At present, we appear to be in one of the later situations, as climate appears to be changing rapidly and is expected to change considerably more over the coming decades.

Current expectations for forest productivity and maintenance of desirable habitat conditions are based mostly on how forests developed under past climate. In general, there is often little acknowledgment of the potential influence of our changing climate on those expectations. Management strategies that ignore the uncertainties associated with climate change are likely to fall short of expectations. Whereas, strategies that acknowledge ongoing climate change, incorporate relevant monitoring, and include capacity for adaptation will likely be more successful in the long run.

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