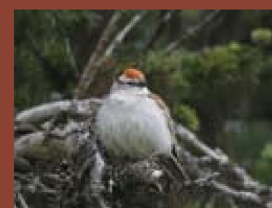
BY RICK BROWN, DEFENDERS OF WILDLIFE,
FOR THE NATIONAL FOREST RESTORATION COLLABORATIVE

The Implications of Climate Change

for Conservation, Restoration, and Management of National Forest Lands



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About the Author

Rick Brown joined Defenders of Wildlife's Northwest office as a senior resource specialist in 2000. Through his graduate studies and work for the USDA Forest Service and the National Wildlife Federation, he has spent more than thirty years working in and for the national forests of the Pacific Northwest and beyond.

About the Project Partners

The National Forest Restoration Collaborative is comprised of environmental and community-based forestry groups dedicated to providing national leadership to advance comprehensive forest and watershed restoration that is ecologically sound and benefits rural communities.

Defenders of Wildlife is a national, nonprofit membership organization dedicated to the protection of all native animals and plants in their natural communities.

American Lands Alliance's mission is to protect and restore America's forest ecosystems by providing national leadership, coordination and capacity building for the forest conservation movement.

The Ecosystem Workforce Program is in the Institute for a Sustainable Environment at the University of Oregon. Its mission is to build a sustainable society by interconnecting ecological health, economic well-being, and vibrant democracy.

TUPPER ANSEL BLAKE

Executive Summary

THIS PAPER IS BASED ON A REVIEW of key scientific literature on climate change and forests, in particular those aspects that appear to have the most relevance for management and policy related to national forests in the United States. Because policy is at least partly values-based, science cannot determine policy; however, basing policy on science increases the odds that policy will provide the values we seek.

Climate change is under way. It is caused primarily by the release of greenhouse gases (most notably carbon dioxide, CO_2) from the burning of fossil fuels by humans, and it will continue and may accelerate if our use of fossil fuels is not substantially reduced. Changes in climate are altering forests and will inevitably cause further, more dramatic changes both directly—through the direct responses of trees to altered temperature and moisture—and indirectly—through shifting patterns of fire, insects, and disease, which are generally expected to increase in extent and severity. While some of these changes may prove beneficial, most will adversely affect the values we derive from forests. Strategies to reduce the adverse effects of climate change (referred to as adaptation or preparation) are being developed, but there is much to be learned. Early actions to mitigate climate change will be more beneficial than later efforts.

Forests will be affected by climate change, but they may also help to mitigate it. Forests influence the rate and extent of climate change by absorbing CO_2 from the atmosphere and storing it in wood and soils or by releasing CO_2 to the atmosphere. CO_2 is released whenever land is converted to nonforest uses or disturbed by logging, burning, or outbreaks of insects and disease. All living forests both absorb and release CO_2, and the relative balance between the two processes determines whether a forest is a source or sink of CO_2. Forests are not the solution to climate change, but they can make important contributions. They will be most effective in mitigating emissions in the near term (the next decade or two), which climate scientists have identified as a crucial period if we are to avoid potentially catastrophic changes in climate.

Climate change is a new and essential consideration for management of national forests, but it can be integrated with the other values of these forests. Often, but not always, these values support one another and the integration is synergistic. Similarly, carbon storage is an important aspect of the role of forests in climate change, but it is not the only one. The goal of carbon storage must be integrated with climate-adaptation strategies as well as traditional goals such as water, wildlife, recreation, and wood products.

A heavily promoted option for storing carbon involves intensive, short-rotation forest management to produce long-lived wood products. Studies consistently show, however, that due to the inevitable inefficiencies of converting trees to wood products, this approach will store less carbon than simply letting the forest grow. Factoring in losses of carbon from the conversion of mature and old-growth forests, which is how virtually all managed forests begin, shows this option to be even less favorable. Substituting wood for more energy-intensive materials such as concrete might be beneficial, but the benefits of such substitution cannot be measured reliably, and should not be presumed without effective public policies to ensure that substitution occurs.

Any accounting of forest carbon needs to quantify all the various component carbon pools—live trees, other vegetation, dead trees (coarse, woody debris and snags), forest floor, and mineral soil—and the fluxes of carbon to and from these pools. For policy considerations, it will be most fruitful to consider these pools and fluxes over landscape scales and time frames of at least several decades. Increasing either the frequency or severity of disturbance will generally lower carbon stores. Annual carbon emissions in the U.S. from logging and wood processing exceed those from forest wildfires.

Managers have conducted thinning and fuels reduction in dry, fire-prone forests for a variety of reasons, and preparing for warmer and drier conditions with climate change can now be added to the list. The implications of such treatments for carbon storage needs further research, but it appears that the net effect, whether positive or negative, may be relatively small. This is probably also true for thinning in moist forests to improve yields or habitat. Postfire salvage logging can be expected to increase net carbon emissions. While planting trees after fire may temporarily increase rates of carbon storage, possible effects on long-term productivity and vulnerability to reburn need to be taken into consideration.

Conventional notions of restoration to presumed "presettlement" conditions will become increasingly dubious as climate changes. In the near term, restoration treatments such as those intended to improve fire and drought resilience in dry forest landscapes are also consistent with preparing for warmer and drier conditions and increased likelihood of fires and insect outbreaks.

Strategies for conserving biological diversity will need to be modified to incorporate consideration of climate change, such as reconsidering which species may be of greatest concern, or size, number, and location of protected areas. However, most of what needs to be done soon is what we've known we need to do for a long time: reducing habitat fragmentation, increasing populations of at-risk species, and controlling invasive species. Conservation strategies need to recognize that species can be expected to move and adapt independently as climate changes, and that novel ecosystems will arise.

Some of the greatest challenges in responding to the threats of climate change may arise from the disconnect between the nature and pace of those threats and the governmental and social institutions available to address them. Although human-caused changes in climate are remarkably fast by climatological standards, they are slow compared to budgeting, planning, and electoral cycles. The fragmented, "stove-piped" approaches typical of natural resource management will need to be overcome if the ecologically cross-cutting challenges of climate change are to be met. The term "adaptive management" is burdened with a history of failure, but the learning-by-doing principles it embraces will need to be put to work if we are to have any chance of successfully addressing climate change.

Although the challenges appear daunting, key scientists and economists provide reasons to believe that they can be met, but only if interested citizens, managers, scientists, and elected officials unite with a sense of common purpose.

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USDA–FOREST SERVICE

CREATIVE COMMONS / ALASKAN FRANK

CLIMATE CHANGE IS COMING to a national forest near you. How much forests will be altered as a result of climate change largely depends on how much humans reduce their emissions of greenhouse gases and how quickly. The effects of climate change on national forest lands will also depend in part on how forest management responds to these threats.

This paper is an attempt to summarize the key scientific literature on climate change and forests, in particular those aspects that appear to have the most relevance to management and policy related to national forests in the United States. Topics explored begin with those relating to forests as ecosystems—forests and carbon; forests and climate change; drought, insects, and fire; and soil and water—and continue with those more directly relating to forest management—wood products, thinning, fuels-reduction and fire, restoration, and strategies for conserving biological diversity. Obviously, the conclusions one can draw from this type of overview will be general, but they should provide a basis for reconsidering both management objectives for national forest lands and how those objectives might best be met. Definitive answers are often lacking, but successful pursuit of solutions needs to begin with properly posed questions.

The discussion that follows accepts the strong scientific consensus that humans have altered (and are continuing to alter) Earth's climate by emitting greenhouse gases (most notably, carbon dioxide, CO_2). Full explanations of the scientific evidence for this conclusion and its implications can be found elsewhere[1]. Increased concentrations of greenhouse gases are causing Earth's atmosphere to warm, though not uniformly. This warming threatens to cause Earth's climate to depart significantly from the conditions humans experienced over the last ten thousand years, while they developed agriculture and civilization. "Anthropogenic global heating and climate disruption" probably most accurately describes what is happening, but, for the sake of brevity, this paper will generally refer to these human-caused disturbances simply as climate change. Climate varies naturally as well, but that is not the focus here.

In the realm of science, skepticism is not just encouraged, it is essential, and appropriately skeptical scientists will continue to refine our understanding

1 The Real Climate website (www.realclimate.org) is a good general resource and their "Start Here" section (http: //www.realclimate.org/index.php/archives/2007/05/start-here/) provides a very useful collection of links to information for those with varying levels of background.

Some Relevant Basics of Climate Change

GREENHOUSE GASES

For more than 100 years, scientists have known that some trace gases in the atmosphere—most notably water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)—are responsible for maintaining Earth's temperature at about 33° C warmer than it would otherwise be. The term "greenhouse gas" has been applied to these gases for a very long time, and although the analogy between how they warm the Earth and how glass warms a greenhouse is deeply flawed, the name has stuck. More greenhouse gases means more warming, and humans have been adding these gases, especially CO_2, to the atmosphere through burning fossil fuels, deforestation, and the manufacture of cement. Since the beginning of the industrial age (usually defined as 1750, with high levels of fossil fuel use taking off around 1850, which is also the beginning of instrumental temperature records), these increases have caused average global temperature to increase by 0.7° Celsius (C) or 1.3° Fahrenheit (Trenberth et al. 2007).

These changes inevitably affect plant and animal species. There is considerable evidence that species have responded to climate changes through alterations in geographic and elevational distribution and the annual timing of their life cycles (Rosenzweig et al. 2008; Beckage et al. 2008; Parmesan 2006; Parmesan and Yohe 2003; Walker and Steffen 1997; Root et al. 2003; Lenoir et al. 2008). These responses may exceed populations' ability to adapt, to the detriment of the species directly involved or for those with which they interact (Lanchbery 2006; Gitay et al. 2002), for instance when flowers bloom before their insect pollinators emerge in the spring.

Carbon dioxide represents about 80 percent of the human-caused emissions of greenhouse gases (Bernstein et al. 2007), and is the major greenhouse gas of concern in exchanges between forests and the atmosphere. This paper follows the convention of using the term "carbon" generically when referring to the movement of carbon or carbon-containing compounds through the carbon cycle, specifically flows between forests and the atmosphere. When a forest (or anything else) absorbs carbon from the atmosphere, it acts as a "sink"; if it releases carbon to the atmosphere, it acts as a "source." Trees and other plants, and thus forests, absorb carbon dioxide from the atmosphere during photosynthesis and also release it through respiration, decay, and fire; the difference between rates of absorption and release determines whether a forest is a net sink or a net source.

COMMITMENT, PROCRASTINATION, AND THE TIME VALUE OF CARBON

The oceans warm more slowly than the atmosphere and thus, for a given increase in CO2, there is lag of a few decades in overall warming (Hansen et al. 2005). A significant portion of added CO2 persists in the atmosphere for at least hundreds and more likely thousands of years (Archer 2005; Montenegro et al. 2007). So, although we have seen a 0.7° C warming thus far, the amount of CO_2 already added to the atmosphere since 1800 virtually guarantees that there will be another 0.7° to 1.0° C warming over the next few decades, while the oceans "catch up." This "climate change commitment" (Wigley 2005) means that the CO_2 we add to the atmosphere today will continue to change the climate for at least many hundreds of years.

A related concept has been referred to as the penalty of procrastination (Socolow and Lam 2007) or "procrastination regret" (Keller et al. 2007). Because CO_2 accumulates in the atmosphere, current emissions make it all the more difficult to meet targets for limiting total atmospheric CO_2 or global temperature in the future. Thus, just as there is a time value to money, there is a time value to carbon (Richards 1997). As Malhi et al. (2002) put it, "Carbon absorbed early in the century has a greater effect on reducing end-of-century temperatures than carbon absorbed late in the century. . . . to be relevant, a forest-carbon sequestration programme has to absorb most of its carbon within the next few decades."

DANGEROUS INTERFERENCE AND SURPRISES

In 1992, the United Nations adopted the "Framework Convention on Climate Change," which included the objective of limiting atmospheric greenhouse gases to avoid "dangerous anthropogenic interference" with climate. A variety of governments, nongovernmental bodies, and scientists have subsequently examined the question of what constitutes a dangerous change in climate and what levels of greenhouse gases would precipitate such a change (Baer and Mastrandrea 2006; Dixon 1997; Hansen et al. 2007; Hansen 2007; Pyke and Andelman 2007; Tirpak et al. 2005; Sci-

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entific Expert Group 2007; Graßl et al. 2003). An increase in global temperature of 2° C or greater has most often been identified as a threshold (or "tipping point") above which effectively irreversible changes become highly likely (Hansen and Sato 2007). Some researchers (Lenton et al. 2008) have identified more than a dozen potential "tipping elements" spanning the globe, including dieback of both boreal and Amazon forests. The level of atmospheric CO_2 corresponding to a 2° C rise would be reached in as little as two or three decades at current rates of emission.

Earth's climate system is highly complex and nonlinear, and seemingly small changes may well lead to additional positive feedbacks[1] that could trigger abrupt and dramatic shifts. As the National Research Council (2002) observes, "it is likely that climate surprises await us." For example, relatively small changes in greenhouse-gas levels and global temperatures can cause major changes in patterns of ocean circulation or precipitation (Lenton et al. 2008; Rial et al. 2004). As a result, even a gradually changing climate may lead to dramatic, perhaps irreversible, changes in natural systems (Burkett et al. 2005). The more rapidly climate changes, the more likely are disruption and surprise (Root and Schneider 1993). Coping with these likely surprises "may be one of the greatest challenges of future global change" (Hansen et al. 2001).

All in all, this information tends to paint a rather grim picture. However, James Hansen, arguably the United States' foremost climate scientist, continues to believe that there are feasible and realistic strategies that can keep climate change "within manageable bounds" (Hansen and Sato 2007). Others (Pacala and Socolow 2004) have identified a suite of technologies and strategies that, if used in combination, could meet this goal, including improved fuel economy and reduced use of cars, more efficient buildings, wind and solar electricity, as well as increased storage of carbon in agricultural soils and natural ecosystems such as forests.

1 A response that adds to, or amplifies, an initial perturbation away—in either direction—from a baseline condition is referred to as a positive feedback; one that tends to move it back toward baseline, or stabilize, is a negative feedback.

of climate change. However, many lines of evidence confirm that the atmosphere is warming and climate is changing, and the best explanation is that human activities, most notably the burning of fossil fuels, are the cause (Oreskes 2007). This scientific consensus provides the most prudent basis for decisions about public policy and individual behavior.

There are many things about climate change and forests that can be known with a high degree of confidence—the current concentration of carbon dioxide in the atmosphere, or the extent of forest land in the United States, for example. However, there are greater uncertainties about many other measurements, such as how much carbon is stored in these forest ecosystems and how much they absorb and release each year. Nonetheless, there are reasonable conclusions that can be reached based on what we know, while continuing to attempt to refine the underlying knowledge.

By absorbing and storing carbon, forests and other ecosystems can help reduce the rate of climate change, although they can by no means provide a complete solution. And they can provide these benefits now, without the delays inherent in many technological solutions. However, forests and the carbon-storage potential they offer are also vulnerable to climate change.


USDA–FOREST SERVICE

There are management options that can help optimize carbon storage by forest ecosystems while reducing their vulnerability to climate change, but there is also much to be learned about how best to accomplish these goals. Flexibility and adaptability of management responses will be essential, as will be a willingness to follow evidence, not just interests or intuition.

Carbon storage in forests will not prevent climate change, and a focus on climate change should not trump other management objectives. But climate change and carbon storage introduce a new set of values to the ones we traditionally associate with national forests. Management for these new values may converge with other values such as conservation of biological diversity, water, recreation, and sustainable use of products, but not always. Optimizing the balances of these values and uses can be informed, but not determined, by science.

Forests and Carbon Storage

FORESTS PLAY A ROLE in the carbon cycle in several ways. As natural ecosystems, they remove CO_2 from the atmosphere through photosynthesis, storing (sequestering) the carbon primarily as wood and other biomass, and in soil. These stores are referred to as a carbon pool, stock, or reservoir. Globally, forests account for about one-half of terrestrial carbon stores (Malhi, Meir, and Brown 2002), and, taken as a whole, they store carbon in roughly equal amounts above and below ground in the U.S. (Birdsey and Lewis 2003). When trees decay or burn, CO_2 is released back to the atmosphere, some immediately, most more slowly through decay. At large scales, the processes of storage and release of carbon have historically been in approximate balance. Individual forest stands might be killed by fire, wind, insects, or disease, but over landscapes, balances of growth, decay, and combustion would produce a characteristic level of carbon storage. Over long periods of time, climate, resulting disturbance regimes, and thus the relative balance of carbon stores, would change (Smithwick, Harmon, and Domingo 2007). Thus, forests were one of the mechanisms that helped maintain fairly stable concentrations of atmospheric CO_2, and they still remove some of the excess CO_2 from burning fossil fuels.

Clearing for agriculture, beginning around 8,000 years ago, apparently produced a gradual and varying loss of forests in many portions of the Earth (Ruddiman 2003), but extensive deforestation in North America awaited the onset of the industrial age. Industrial conversion, up to 1990, increased global forest loss to 20–30 percent, primarily in the northern hemisphere (Malhi, Meir, and Brown 2002). The resulting CO_2 emissions have contributed about 45 percent of the total increase in atmospheric CO_2 since 1850, and current estimates are that continuing deforestation, primarily in the tropics, is responsible for about 25 percent of current global emissions (Malhi, Meir, and Brown 2002).

In the northern hemisphere, the balance of forest loss and growth shifted starting early in the twentieth century as trees began to reclaim abandoned farms in the eastern U.S. (Houghton and Hackler 2000). Reductions in the use of wood as fuel, reductions in wildfire, and the inadvertent fertilization by nitrogen released in the burning of fossil fuels have also contributed to forests becoming net sinks of carbon (Magnani et al. 2007; Houghton, Hackler, and Lawrence 2000). An opposing trend occurred where logging of old-growth forests, particularly in the Pacific Northwest, led to the release of significant amounts of carbon, even when forests were not converted to other land uses (Harmon, Ferrell, and Franklin 1990). Warmer temperatures, at least where drought is not a problem, have also contributed to increased forest growth, including expansion of northern boreal forest into tundra (Nabuurs et al. 2007).

Estimates vary (King et al. 2007), but it appears that about one-half of the carbon absorbed by terrestrial ecosystems in the conterminous U.S. is absorbed by forests (Pacala et al. 2001), equivalent to around 10 percent of U.S. carbon emissions from fossil fuels (Smith and Heath 2007; Woodbury, Smith, and Heath 2007). Almost one-half of this forest sink may be attributable to national forests (Birdsey and Heath 1995), although these lands comprise only about one-fifth of U.S. forests (Mills and Zhou 2003). Depro et al. (2008) calculated that if all timber harvest ceased on national forests, the rate of carbon storage on those lands could be increased by an average of about 30 percent over the next five decades, compared to a "business as usual" scenario, including stores in wood products. Returning to high logging levels of the 1980s would dramatically lower the rate of carbon storage. Depro et al.'s (2008) estimates include an assumption that future losses to disturbance from fire, insects and disease will be similar to those of the recent past. However, as discussed below, climate change is expected to increase losses due to these factors.

Carbon Dioxide Fertilization

Forest growth and carbon storage may also have been enhanced due to a "fertilization" effect of increased atmospheric CO_2. Along with water, CO_2 is an essential ingredient of photosynthesis. Increased concentrations of CO_2 allow photosynthesis to proceed more efficiently, with plants losing less water for a given amount of CO_2 absorbed through their leaves. Since water stress often limits plant growth, a CO_2-enriched environment supports more growth than would otherwise occur, at least in laboratory or other controlled settings (Norby et al. 2005; Idso and Kimball 1993; Graybill and Idso 1993).

In the real world, with limited water supplies, warming temperatures, deficiencies in other nutrients, or the influence of factors such as ozone that inhibit plant growth, the responses to increased levels of CO_2 are more complex (Asshoff, Zotz, and Korner 2006), and it has been difficult to quantify the extent to which forest growth has been enhanced by increasing levels of CO_2 (Birdsey et al. 2007). Some authors consider this enhancement to be insignificant in comparison to the effects of land use reverting from agriculture to forests (Casperson et al. 2000) and fire exclusion (Hurtt et al. 2002). Even in the laboratory setting, the CO_2 fertilization effect reaches a saturation point, i.e., as the concentration of CO_2 increases, growth benefits slow and then level off. Nonetheless, many researchers assume CO_2 fertilization has contributed to increased storage of carbon by forests during recent decades, and vegetation models often assume that this effect will contribute to future growth, at least for a while. Assumptions about the extent of CO_2 fertilization are one factor that influences whether and how soon these models predict that forests will change from sinks to sources of carbon as climate changes (Bachelet et al. in press; Neilson et al. 2007).

MARCUS KAUFFMAN, RESOURCE INNOVATIONS

Forests and Climate Change

STRATEGIES FOR ADDRESSING CLIMATE change can be grouped into two broad categories:

1. Practices that reduce emissions of greenhouse gases or help remove them from the atmosphere are referred to as *mitigation*.

2. Strategies that attempt to avoid or minimize the adverse effects of past and future climate change are referred to as *adaptation* (or *preparation*).

Improving automotive fuel efficiency or eliminating the emissions from a coal-fired power plant by replacing it with wind turbines would be examples of mitigation. Examples of adaptation include raising levees or restoring coastal wetlands in anticipation of rising sea levels and more intense hurricanes, or changing agricultural practices to attempt to maintain productivity in the face of more variable weather. Examples from the forest realm would include increasing carbon stores by extending rotations or controlling fire for mitigation, and density management or planting more drought-tolerant genotypes for adaptation.

Because forests can both store and emit CO_2, they can contribute to mitigation strategies. Since their growth is influenced by climate, they should also be addressed in adaptation strategies. Changing our expectations of forests, of what they will be like and what values they will provide as they change in response to climate, could also be considered a form of adaptation (Spittlehouse 2005). Forest management and conservation planning will need to take climate change into consideration and incorporate elements of both mitigation and adaptation. In the absence of adaptive measures to help forests maintain their integrity as climate changes, drought, fire, insects, disease, and invasive species are expected to cause some forest carbon sinks first to weaken and then transform from sinks to sources (Friedlingstein et al. 2006; Nabuurs et al. 2007; Hurtt et al. 2002). These changes can also be expected to alter habitats, watersheds, and other values we derive from forests.

Although sequestration of carbon by forests will not be the solution to human-caused climate change, it should be considered as a potentially significant component of a package of mitigation strategies (Nabuurs et al. 2007; Malhi, Meir, and Brown 2002). The greatest potential contributions are from tropical forests (Malhi, Meir, and Brown 2002), but the

The Popular Press: Read with Care

In early 2006, Keppler (2006) reported research demonstrating that living plants emit methane, which, if true, represented a new biochemical pathway in plants and a previously unknown source of methane, a powerful greenhouse gas. Popular accounts suggested that this effect might overshadow trees' beneficial effects of sequestering carbon and helping to reduce atmospheric carbon dioxide. Some readers got the impression that planting trees would be a bad idea, or maybe that trees should be cut down to help the climate. In a follow-up paper in *Scientific American*, the authors made it clear that the amount of methane they detected would not justify such conclusions, and that as far as they are concerned, "The potential for reducing global warming by planting trees is most definitely positive" (Keppler and Röckmann 2007). Subsequent research has been unable to confirm the methane emissions (Dueck et al. 2007), so there is no basis for letting the unconfirmed findings of Keppler et al. (2006) influence forest policy.

In late 2006, another paper (Bala et al. 2007) made a splash. Many readers of newspaper or online articles came away with the impression that the warming effects of forests (because they have low albedo and absorb more light than other types of vegetation) offset the climate benefits they offer by absorbing CO_2, and that we would be better off cutting them all down (or, as one e-mail subject line read, "deforestation can cool the planet"). The scientific literature has made note of the potentially cooling effects of deforestation for nearly thirty years (Otterman, Chou, and Arking 1984; Sagan, Toon, and Pollack 1979). The work of Bala et al. (2007) is a preliminary attempt to quantify the various and sometimes opposing effects of forests on climate. Their general findings have been reinforced by other recent work (Betts et al. 2007). Although it would be premature to base firm policy decisions on this work, it does suggest that afforestation in temperate latitudes may not provide all the climatic benefits that have been assumed for it, and that in boreal areas afforestation will almost certainly be counterproductive. None of these authors suggest cutting down forests as a policy response, and all acknowledge the many benefits forests provide. Where forests are already growing, it seems appropriate to consider how to optimize their carbon storage, given that different forest management strategies will not have significant effects on albedo. Also, increasing atmospheric CO_2 doesn't just affect climate, it also leads to acidification of the oceans, with potentially devastating effects on coral reefs and other organisms (Orr et al. 2005; Cao, Caldeira, and Jain 2007). Removal of CO_2 from the atmosphere by temperate forests can help reduce these undesirable effects on oceans, even if these forests have less of a beneficial effect on climate than previously thought.

role of U.S. forests is not trivial (Heath and Birdsey 1993; Pacala et al. 2001). For instance, forests in the moist western Pacific Northwest apparently store more carbon per acre than any other forests in the world (Smithwick et al. 2002). Harvest reductions since the late 1980s on national forests in this region, while designed to benefit wildlife, fish, and watersheds, are projected to substantially increase carbon stores (Alig et al. 2006). Forests also have a great potential to help address the procrastination penalty in that they are existing carbon sinks that can buy time (Houghton 2007), or serve as a bridge to the future development and application of policies and technologies to reduce fossil-fuel emissions (Lee, McCarl, and Gillig 2005). Practices that reduce carbon release from established forests, such as fire management and reduced harvest, provide instant results, as opposed to actions such as planting trees on agricultural lands (afforestation), that take many years before effective carbon sinks are created (Krankina and Harmon 2006; Krankina, Harmon, and Winjum 1996).

Albedo and Other Complications

The relationships between forests and climate go beyond the storage and release of CO_2. An important climatic effect of vegetation is its effect on albedo (or reflectivity). Vegetation absorbs light, converting some of the sun's energy to heat, thereby contributing to warming of the atmosphere. This albedo changes most dramatically as dark boreal forests expand into tundra, disrupting highly reflective, continuous snow that covers low-growing vegetation for most of the year. The resulting increased warming enables further expansion of forests in a positive feedback loop. Forests generally have a lower albedo than other vegetation, that is, they absorb more light and thus generate more heat. Therefore, when forests are reestablished on agricultural lands (afforestation), even as they help forestall climate change by absorbing carbon, they contribute to warming by absorbing more sunlight than did the agricultural crops. These relationships are complex and complicated by factors such as the cooling effect of transpiration (Marland et al. 2003; Bonan 2008). Some possible management and policy implications of these relationships are discussed in the sidebar on the popular press.

Drought, Insects, and Fire

Although there is great uncertainty about how forests will respond to changing climate and increasing levels of atmospheric CO_2, the factors that are most typically predicted to influence forests are increased fire, increased drought, and greater vulnerability to insects and disease.

Since at least the 1990s, scientists have predicted that fires would become larger and more frequent as climate changes in the western United States (Miller and Urban 1999; Franklin et al. 1991), and it appears that such a trend is now evident (Westerling et al. 2006). However, this will not be the trend everywhere; in some areas (e.g., Quebec), fires have decreased with changing climate, and this trend is predicted to continue (Bergeron et al. 2001). Westerling et al. (2006) provide evidence that the number and size of fires are increasing in the West, primarily due to lengthening of the fire season as a result of early snow melt and warmer summers. While these researchers present no data on trends in fire severity, they observe that, with forests having grown more dense due to past fire exclusion, fire severity has likely increased as well. Paleoclimatic studies suggest that a warming climate will lead to more severe fires (Whitlock, Shafer, and Marlon 2003; Pierce, Meyer, and Jull 2004), an outcome that has also been predicted by some climate and vegetation models, largely due to increased wind speed with climate change (Fried, Torn, and Mills 2004). Westerling et al. (2006) observe that the "overall importance of climate in wildfire activity underscores the urgency of ecological restoration and fuels management to reduce wildfire hazards."[2]

When forests burn, not all carbon in a fire ends up as emissions to the atmosphere. Not only can dead trees persist for decades (Krankina and Harmon 1995), but charcoal, or black carbon, the product of incomplete combustion, is highly resistant to decay and can persist in soils and sediments for centuries (Leenhouts 1998; Johnson and Curtis 2001). This charcoal can also help improve the availability of water and nutrients to plants (DeLuca and Aplet 2008). However, there is also evidence that mixing charcoal into soil, at least in boreal forests, can stimulate loss of soil humus, resulting in carbon emissions (Wardle, Nilsson, and Zackrisson 2008). Using midrange values of 10 percent of above-ground carbon consumed by fire (see below), and 5 percent of this converted to charcoal (DeLuca and Aplet 2008), for every ton of preburn above-ground carbon, 200 hundred pounds would be consumed (emitted) and ten pounds would end up as charcoal. DeLuca and Aplet (2008) point out that the cumulative benefits of charcoal from forest wildfire, in terms of both storing carbon and improving soil quality, can be significant over long time frames (millennia), and that these benefits are not often considered in fire-management policy. These observations are important, but consideration of the time value of carbon may suggest a different weighting of the tradeoffs between carbon emissions from fire and the benefits of charcoal, at least over the next few decades. Policy decisions about the appropriate uses of fire and fire suppression will continue to be complex (Noss 2001).

BRUCE TAYLOR

Climate change has also been predicted to affect the dynamics of forest insects and diseases (Franklin

2 The extensive literature on where restoration and fuels management may be most appropriate and how they might be best accomplished will not be reviewed here; see, for instance, (Noss et al. 2006; Brown, Agee, and Franklin 2004).

et al. 1991), and these effects are becoming apparent. As Logan and Powell (2005) observed, "all aspects of insect outbreak behavior will intensify as climate warms." One example involves drought, increased temperatures and the *Ips* beetle in pinyon pine in the Southwest (Breshears et al. 2005; Burkett et al. 2005; Allen 2007). Although drought is common in this region, in the late 1990s the effects of drought were exacerbated by elevated temperatures, causing trees to be more vulnerable to attack by *Ips* (a type of bark beetle), leading to abrupt dieback on over 12,000 km^2 (3,000,000 acres, or about three times the size of the state of Rhode Island). Mortality of dominant pinyon pine often exceeded 90 percent, even at higher elevations (Breshears et al. 2005). The effects of the drought and elevated temperatures on these forests may have been exacerbated by increased stand densities that developed during higher-than-normal precipitation in the preceding twenty years or so (Breshears et al. 2005). This is consistent with predictions from climate and vegetation models indicating that climate change may lead to periods favorable to forest growth (due to warmer temperatures, increased precipitation, increased CO_2), followed by extreme drought and forest dieback over large areas (Neilson et al. 2007). Elevated CO_2 levels can also favor insects, such as the *Ips* beetle, that feed on trees' phloem (Whittaker 1999). One of the other results of the drought was increased erosion (Breshears and Allen 2002). Some of the carbon in eroded soil remains in sediments, but some is lost to the atmosphere (Breshears and Allen 2002).

Mountain pine beetles often attack lodgepole pine, with larger trees typically over eighty years old being most vulnerable (Taylor et al. 2006). In western Canada, fire suppression during the twentieth century increased the extent of lodgepole forests dominated by older trees, warming temperatures have lead to greater over-winter survival and summer growth of bark beetles, and drought has increased the vulnerability of trees to attack by bark beetles (Taylor et al. 2006). This combination of factors has led to an outbreak of bark beetles that dwarfs any previously recorded, turning these forests from small sinks to major sources of carbon to the atmosphere (Kurz et al. 2008). While recovery may well allow these forests to again become carbon sinks, increasing temperatures and changing fire regimes make this uncertain (Kurz et al. 2008; Kurz, Stinson, and Rampley 2007). Mountain pine beetles are also showing increased activity in lodgepole pine in the U.S. and now pose a significant threat to high-elevation whitebark pine in the Rocky Mountains (Logan and Powell 2001). A similar set of factors led to dramatic outbreaks of spruce beetle in spruce forests in Alaska in the late twentieth century (Berg et al. 2006).

Although it is widely assumed that insect-caused mortality leads to an increased likelihood of severe fire, the evidence for such a cause-and-effect relationship is mixed (Fleming, Candau, and McAlpine 2002; Parker, Clancy, and Mathiasen 2006; Romme et al. 2006; Hummel and Agee 2003; Bebi, Kulakowski, and Veblen 2003). It appears that in lodgepole pine forests in the Rocky Mountains, there may be an increased probability of severe fire only if ignition occurs while dead needles are still on the trees (Romme et al. 2006). Fleming et al. (2002) found an increased likelihood of fire three to nine years after spruce budworm defoliation in Ontario, apparently due to the accumulation of surface and ladder fuels as killed trees broke and fell; as these fuels decayed further, fire risk declined. A recent review article (Jenkins et al. 2008) confirms that there is considerable variability and uncertainty about these relationships, which vary with forest type, but also indicates that the connections between insect outbreaks and fire risk and hazard may be stronger than some earlier papers have suggested.

The effects of increased insect outbreaks and subsequent fires on carbon storage may still be less than those associated with traditional forest management. When a forest burns, the majority of its biomass remains, to be slowly released through decay. Carbon emissions from fire vary widely, depending on pre-fire conditions and the intensity of the fire. While timber harvest removes 50–80 percent of a forest's total above-ground woody biomass (some of which goes to wood products, while most of the carbon is released to the atmosphere), fires consume a small fraction of this (Gower 2003). Estimates put this fraction in the range of 5–20 percent, equivalent to perhaps 5–15 percent of the total above-ground woody biomass (Campbell et al. 2007; Fahnestock and Agee 1983; Wayburn et al. 2000, 2007).

Soil and Water

Forest soils store significant amounts of carbon (typically roughly equal to that above ground) and this storage can be much more stable than that in vegetation (Gower 2003). However, there appears to be considerable uncertainty about the dynamics of this pool. Soil carbon is inherently variable and difficult and time-consuming to measure, and the literature (not to mention some individual papers) is inconsistent as to whether "soil" refers only to mineral soil or also includes the forest floor (duff and litter). General reviews—assessing broad geographic regions or the U.S. as a whole, and considering time spans of several decades—often assume mineral soil carbon is quite stable (Johnson 1992). This appears reasonable for that level of analysis, but it is important to bear in mind that some forest-management practices can have significant effects on soil carbon, depending on the equipment used and the intensity of removal (Jarvis, Ibrom, and Linder 2005; Heath and Smith 2000). There is some evidence that the longer a forest goes without disturbance, the more carbon will be stored in its soil, and gradual accumulation can continue for centuries (Entry and Emminghan 1995; Zhou et al. 2006; Schulze, Wirth, and Heimann 2000; Pregitzer and Euskirchen 2004). Conversion of old-growth forests to short-rotation plantations leads to declines in soil carbon (Seely, Welham, and Kimmins 2002). Also, as temperatures rise, the activity of soil organisms may increase, accelerating rates of decay of soil organic matter and thus the release of CO_2—another potential positive (amplifying) feedback loop of climate change about which there remains considerable uncertainty (Houghton 2007).

Carbon storage in soils can also be affected by changes in vegetative cover types. In many different areas, trees have been expanding into nonforest settings, including grasslands, sagebrush-steppe, prairie, and mountain meadows. Various factors, including fire exclusion, livestock grazing, warming climate, and increased atmospheric CO_2 contribute to this encroachment of trees, though the relative contributions of each varies in different settings. While conversion to tree-dominated vegetation types may eventually lead to increased carbon storage, sometimes the short-term trend (the first decade or so after tree expansion begins) is for carbon levels to decline due to losses from the soil (Pacala et al. 2007; Jackson et al. 2002).

Soil characteristics influence the availability of moisture for plants as well as runoff of water and water quality. As Breshears and Allen (2002) observed in the Southwest, drought associated with changing climate can reduce vegetative cover, leaving soil more prone to erosion. Both predictions and observations also indicate that changing climate will cause more rain to fall in extreme events (Kunkel 2003; Tebaldi et al. 2006), which will increase the risk of erosion. Such events are likely to exceed design standards for existing road and drainage systems (Mote et al. 2003), further increasing risks of sediment delivery to streams and degradation of aquatic habitat.

Increasing air temperatures will translate to increased water temperatures, which will be detrimental to coldwater fish (such as salmon, trout, and char) in many areas (Carpenter et al. 1992). Since sunlight can also increase stream temperatures, more conservative treatment of riparian zones may be required to maintain shade in order to limit increases in stream temperatures (Moore, Spittlehouse, and Story 2005).


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Restoration of Beaver Habitat

One adaptive strategy that has been proposed for these changing patterns is to restore habitat for, and populations of, beaver. Beaver dams can slow runoff and increase late-season stream flows. Suitable beaver habitat, i.e., well-vegetated stream banks with abundant shrubs and deciduous trees, may also increase resistance to stream bank erosion from high runoff associated with extreme precipitation events. Habitat that is improved to support beavers will also support other species, and beaver activity can be expected to further diversify habitats, all in a setting that becomes more resilient to the stresses of climate change. There is one cautionary note regarding beavers: their ponds collect sediments that include carbon-containing compounds, which, as they decay, will be emitted as carbon dioxide and methane (Varekamp 2006). Methane has a global warming potential at least twenty-five times stronger than CO_2 (even greater at shorter time frames) (Forster et al. 2007). An assessment of the significance of this side-effect would require an estimate of likely increases in beaver impoundments, the associated accumulation of sediments, and resultant emissions over different time frames.

Predicted and observed decreases in snowfall, particularly in mountainous regions of the West (Mote et al. 2005), will also have effects on forest streams and hydrology. Whether overall precipitation is expected to increase, decrease, or remain the same varies with location and depends on which climate models are used. However, reduced precipitation as snow will mean earlier peak flows and lower late-summer flows in areas where the majority of precipitation falls in the winter.

Forest Management and Carbon

Storing Carbon in Wood Products or Forests?

Given the seriousness of the problems associated with climate change, the need to take mitigation actions sooner rather than later, and the ability of forests to sequester carbon immediately, careful consideration must be given to strategies that optimize the storage of carbon in forests. However, strategies to optimize carbon storage must also consider other, sometimes competing, objectives of forest management (Birdsey 2006; Canadell and Raupach 2008) such as conservation of biological diversity, water, forest products, and recreation.

Some of the terminology used in discussions of how to account for carbon in the manufacture and use of wood products can be confusing. Both "storage" and "sequestration" can be used with dual meanings, referring to both active absorption of CO_2 and the maintenance of pools of carbon. In general, the term sequestration is used to refer to processes, activities, or mechanisms that remove CO_2 from the atmosphere and store it in some stable form such as wood or marine sediments. Growing forests usually are sinks that remove carbon from the atmosphere and store it in the form of wood and in soils as products of wood decay. Manufacturing wood products or placing wood products in landfills involves removing wood from the forest pool and processing and relocating that wood. Not only does this transfer and processing not remove any more carbon from the atmosphere, it releases carbon *to* the atmosphere, both from the forest pool and from burning fossil fuels. It is not altogether surprising that wood in products and landfills are often described as separate pools (though they are just subsets of the forest pool, processed and moved to another location), but it is questionable to refer to wood product manufacture and use as "sequestration." These actions not only fail to remove carbon from the atmosphere but generally lead to more emissions than if the wood were left as part of the forest pool. Much of the carbon may still be stored, but the result is a net increase in atmospheric carbon.

One proposed strategy for maximizing carbon storage involves intensive, short-rotation harvest and storage of carbon in wood products. Proponents of this strategy emphasize the high rate of carbon uptake by young trees, as well as the advantages that may accrue over time if long-lived wood products are substituted for fossil-fuel-intensive products such as concrete, steel, and aluminum. The inherent inefficiencies in converting trees to wood products ensure that carbon storage in wood products will be less than in an undisturbed forest. The only reason this strategy appears to have carbon and climate benefits is that it presumes that wood is substituted for other products (Perez-Garcia et al. 2005), thus reducing overall carbon emissions. The manufacture of cement, a basic component of concrete, emits substantial amounts of CO_2 and accounted for 3.8 percent of anthropogenic releases in the U.S. in 2005 (Hansen and Sato 2007). Using less cement would certainly be beneficial. However, with no limit (regulatory or otherwise) on total construction or use of construction materials, with open markets for both wood and concrete, and with no policies to favor use of wood instead of concrete (for example, through building standards or a carbon tax), there is no way to determine whether substitution is occurring, let alone quantify it. For a product-substitution scenario to be usable in a public-policy context, it will first need to meet the same criteria as any other carbon-offset program–baseline, additionality, leakage, and permanence.[3]

Even if substitution were to occur, its presumed benefits are less than they might appear because they are cumulative and would, even by the proponents' calculations, exceed the carbon storage of an unharvested forest only after several decades. Heath and Birdsey (1993) originally hypothesized that the total carbon storage from harvesting and wood products

3 Generally, for an activity to be credited as a carbon offset, it must: 1) be "additional" in that it reflects a carbon benefit that would not occur without the activity (the scenario without the activity is the "baseline"); 2) be "permanent," which is often taken to mean lasting for at least 100 years; and 3) avoid "leakage," which would occur if the activity led to carbon emissions elsewhere. See, for instance, Cathcart and Delaney 2006.

would exceed that of an unharvested forest, but found that, even over a ninety-year time frame, the no-harvest scenario stored more carbon. Given the time value of carbon, storage by unharvested forests in the near term provides greater benefits than predicted storage in wood products in the future. Since the later storage (avoided emissions, actually)—based on substitution—is doubtful, the carbon advantages of forest growth over harvest and wood products are even more clear.

The rationale for the intensive-harvest and wood-products model has other flaws as well. Proponents assert that there is little if any increase in carbon storage in forest stands over 120 years in age (Wilson 2006). Despite the virtual elimination of old-growth forests in the eastern U.S., Europe, and elsewhere, evidence contrary to this claim can readily be found in research documenting significant increases in carbon stores in mature and old forests in a wide variety of forest systems: Douglas fir–western hemlock, Washington (Harmon et al. 2004; Paw U et al. 2004; Janisch and Harmon 2002); Oregon (multiple forest types, statewide) (Van Tuyl et al. 2005); Douglas fir, Pacific Northwest, west side (Mills and Zhou 2003); ponderosa pine, central Oregon (Law et al. 2003); whitebark pine–subalpine fir, northern Rocky Mountains (Carey et al. 2001); spruce, central British Columbia (Fredeen et al. 2005); northern hardwoods–conifer, New York (Keeton, Kraft, and Warren 2007); hemlock-hardwood, upper Midwest (Desai et al. 2005); eastern hemlock, Massachusetts (Hadley and Schedlbauer 2002); hardwoods, eastern

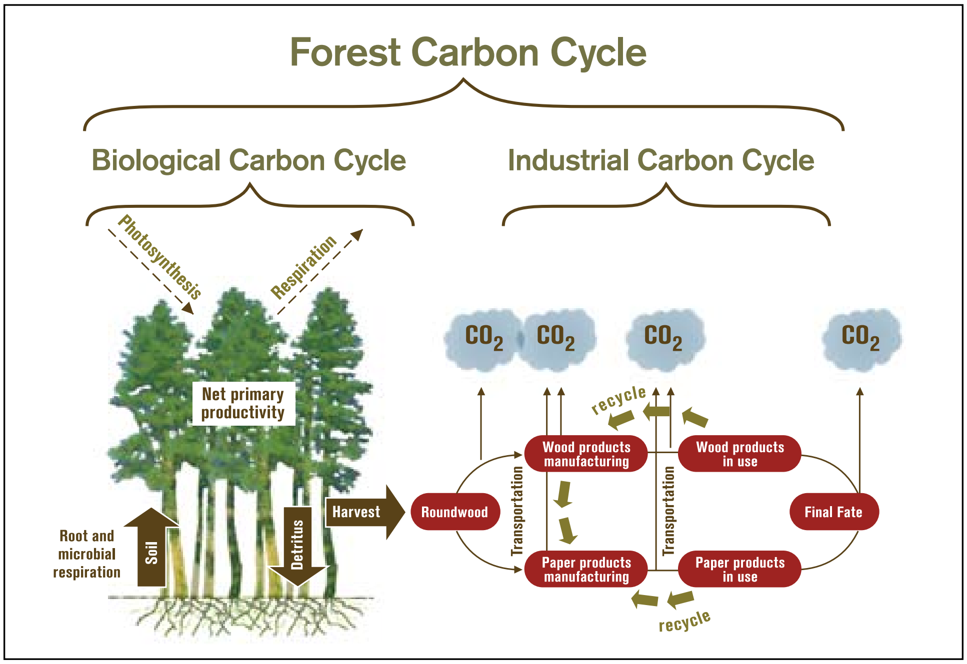

Figure 1. *The forest carbon cycle. Adapted from Gower, 2003.*

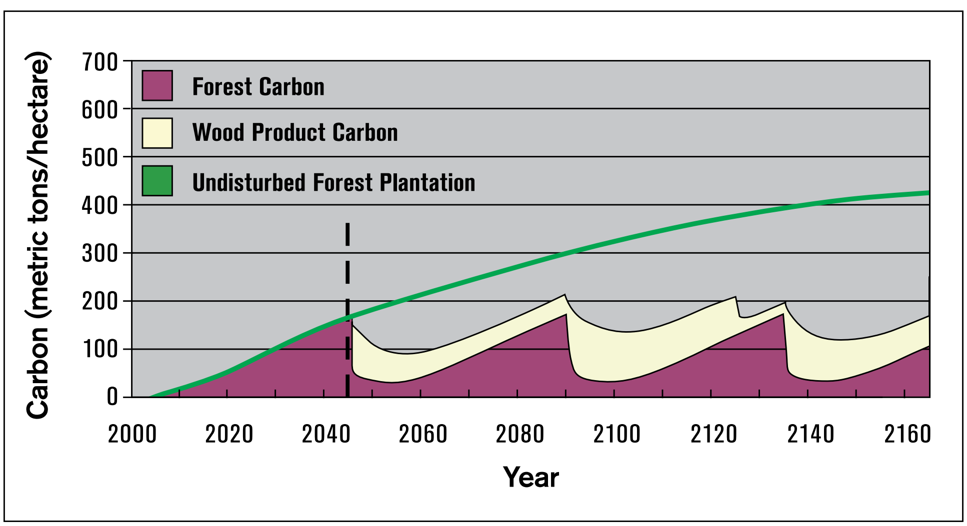

Figure 2. *Forest, wood product, and substitution pools with clear-cut harvest and forty-year rotation. Adapted from Wilson, 2006.*

U.S. (Brown, Schroeder, and Birdsey 1997); beech, central Germany (Knohl et al. 2003); Scots pine, Siberia (Wirth et al. 2002); and multiple forest types, worldwide (Pregitzer and Euskirchen 2004; Lugo and Brown 1986; Buchmann and Schulze 1999).

When analyzing the effects of a forest management scenario on carbon balances, it is essential to consider the difference in carbon stores between the beginning and ending points (Harmon and Marks 2002; Krankina and Harmon 2006). Proponents of the intensive-management option typically assume that initial carbon stores are zero, which is virtually never the case with production forestry since it takes place on previously forested land. If a forest stand originated from planting in a low-carbon system such as an agricultural field (afforestation), the carbon outcomes will be positive. If it originated from logging an old-growth forest (even in the past), carbon stores in the managed stand may never reach the original levels, leaving an unpaid "carbon debt" (Janisch 2001).

A proper accounting of carbon in forest management also needs to consider all pools (trees, other vegetation, snags and logs, litter, duff, and soil) and all fluxes of carbon (to and from live and dead vegetation and soils, due to decay and fire, and those associated with harvest and manufacture, including the burning of fossil fuels) (Harmon 2001). Various spatial and temporal scales should be considered as well, though the long-term and landscape scales will be most useful when considering forest carbon policy (Harmon 2001). At these scales, the characteristic severity and timing of disturbance (such as fire or harvest) determine the overall carbon storage of the landscape (Smithwick, Harmon, and Domingo 2007). Increasing the frequency or severity of disturbance, or both, will lead to lower carbon stores (Birdsey et al. 2007). Typically, intensive forest management reduces carbon stores by increasing both the frequency and intensity of disturbance. The dead wood store of carbon, especially large snags and logs, is particularly likely to be reduced under intensified management (Krankina and Harmon 1995; Fleming and Freedman 1998), which will also have significant adverse effects on forest biodiversity (Freedman et al. 1996; Harmon et al. 1986; Maser et al. 1988).

Old-growth forests, especially in the Pacific Northwest, store large amounts of carbon in live and dead trees, as well as the forest floor (Smithwick et al. 2002). When forests are clear-cut logged, one-half to two-thirds of this carbon is released to the atmosphere immediately or within a very few years as the direct result of logging, the burning and decomposition of logging slash during manufacture of wood products, and the decay of short-lived wood products (EPA 2005; Harmon et al. 1996). This carbon debt will take centuries to repay through the growth of subsequent forests (Harmon, Ferrell, and Franklin 1990; Krankina and Harmon 2006). Scientists have repeatedly concluded that logging old-growth forests to turn part of them into wood products and convert their sites to plantations is a "losing proposition" (Vitousek 1991) that will release large and essentially unrecoverable amounts of carbon to the atmosphere (Harmon, Ferrell, and Franklin 1990; Janisch and Harmon 2002; Krankina, Harmon, and Winjum 1996; Musselman and Fox 1991; Schulze, Wirth, and Heimann 2000). Various researchers have estimated that a landscape dominated by mature and older forests will store from three to five times as much carbon as one dominated by intensively managed plantations (Cooper 1983; Fleming and Freedman 1998; Harmon and Marks 2002).

Furthermore, the carbon emissions associated with the harvest and manufacture of wood products are not trivial. News stories in late 2007 highlighted estimates that burning vegetation (including agricultural burning, prescribed fires, and wildfires in both forest and nonforest ecosystems) in the United States during 2002–6 released carbon dioxide equivalent to 4–6 percent of all human-caused emissions nationally (Wiedinmyer and Neff 2007). Although Wiedinmyer and Neff (2007) do not provide an estimate of emissions just from forest wildfires, it appears that the emissions of forest carbon as a result of logging and wood-products manufacture are of a similar magnitude, and must exceed the emissions attributable to forest wildfires[4]. The emissions as-

4 This calculation starts with 191,629 thousand metric tons, the mean annual dry weight of roundwood (logs) removed from U.S. forests between 2001 and 2005 (Howard 2007). More biomass is harvested in the forest than is removed as logs. Birdsey (1996) provides figures for the ratio of total harvest to harvest removed for both hardwoods and softwoods, for different regions in the U.S. Averaging across types of trees and across regions provides an average ratio of 1.525, which gives a total harvest of 292,234 thousand metric tons of biomass, or approximately 146,117 thousand metric tons of carbon. Multiplying this figure by 50 percent and 67 percent (the range of estimates of total harvested biomass that is released at or near the time of harvest (EPA 2005)) yields 73,058 to 97,898 thousand metric tons, or 73 to 98 Tg of forest carbon emitted annually as a result of timber harvest and processing. A more detailed accounting, such as that done by Winjum et al. (1998) would yield a higher estimate. Wiedinmyer and Neff (2007) estimate emissions from all fires to be 80Tg of carbon.

sociated with logging and processing of wood products calculated here are about three times those from forest wildfires as independently estimated by the Environmental Protection Agency (Smith and Heath 2007). Estimates at smaller scales—for instance, the state of Oregon (Law et al. 2004; Turner et al. 2007) or Shasta County, California (Pearson et al. 2006)—also indicate that annual emissions from logging and wood-products manufacturing typically exceed those from wildfire.

Emissions from fire and logging, because they are from the terrestrial ecosystems pool of carbon (rather than the geologic pool of fossil fuel), can presumably be recaptured over time if forests are allowed to regrow. However, the tradeoffs that result from the time value of carbon should be considered. Both wildfire and production of wood products involve a pulse of emissions over a short period of time, followed by a slower release of carbon as wood decays in the forest, in use as products, or in landfills. Calculations at the level of a forest stand, starting from the time of establishment, indicate that a forest regenerating after fire or logging will typically continue to be a source of carbon for a decade or more until growth of newly established trees begins to overtake the rate of emissions from the decay of organic matter carried over from the previous stand. This period is extended if trees are slow to establish or grow (less carbon uptake) or if there is more coarse, woody debris at the time of stand establishment (more emissions from decay) (Janisch and Harmon 2002).

Postfire Salvage Logging

Postfire salvage logging, because it adds the short-term carbon releases of logging and wood processing, effectively increases the initial pulse of emissions from fire (Law et al. 2004; Krankina and Harmon 2006; Kurz et al. 2008). Some of the emissions associated with logging green forests are from accelerated decomposition of organic matter (fine roots, litter, duff, needles), some of which can also be consumed or killed by a wildfire. Emissions attributable to postfire salvage logging might therefore be somewhat less than those for typical harvest of a green forest. On the other hand, exposed mineral soils can be more vulnerable to logging disturbance postfire, potentially increasing emissions from that source. Salvage logging can interfere with regeneration of trees (Donato et al. 2006), which could further postpone development of an effective net carbon sink. Nitrogen-fixing plants such as shrubs in the genus *Ceanothus*, which often flourish after fire, can help

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increase soil carbon and also improve subsequent growth of trees, thus increasing long-term carbon storage (Johnson and Curtis 2001; Johnson et al. 2004). Artificial planting of trees postfire might accelerate the development of a forest carbon sink, but calculations would need to consider any detrimental effects on long-term productivity of eliminating or shortening the shrub stage. If funding for planting is derived from salvage logging, the presumed future benefits of increased sequestration need to consider the emissions from salvage logging and any detrimental effects on nitrogen-fixers and other pioneer plants or on soils.

There is also some evidence suggesting that postfire salvage logging and planting can create forests that are more prone to high-severity fire if the area reburns (Thompson, Spies, and Ganio 2007). Creating forests that are more vulnerable to disturbance, combined with the likelihood that continuing climate change will increase the probability of such disturbances, could have very undesirable synergistic effects. A regenerating forest can offset the emissions from decomposition following fire, insects, disease, or storms. However, increases in the frequency, severity, or both of such disturbances can lead to a landscape that stores less carbon, effectively causing a long-term net release of carbon to the atmosphere (Chambers et al. 2007).

In summary, carbon stores in forests are vulnerable to the vicissitudes of fire, wind, insects, and the subsequent decay of trees. Houses and other long-lived wood products are vulnerable to the same factors, and also to the vagaries of style and renewal. The anticipated stores in both forests and wood products need to be discounted to account for potential loss. The accounting needs to be as complete and accurate as possible, and to include associated activities such as clearing land to allow construction as well as burning of (or substituting for) fossil fuels. Rigorous accounting may produce results that are contrary to first impressions.

Thinning

Thinning of stands has long been used to increase production in commercial forests. Thinning can be done for a variety of other purposes such as reducing risk of fire or stress from competition among trees, and also as a way of diversifying forest structure and composition in support of other values such as biodiversity (Carey 2003). Although there are a great variety of approaches and intensities covered by the term "thinning," the immediate effect of all of them will be a reduction in forest carbon stores that may or may not be recovered over time (Cooper 1983; Krankina and Harmon 1994). With the exception of extremely dense stands of some species, the more dense a stand, the more woody biomass it will produce (Schroeder 1991; Tappeiner, Maguire, and Harrington 2007). However, although the biomass (and thus stored carbon) of a thinned stand will likely be less than that of an unthinned one, growth after thinning will be concentrated on the remaining trees, and a thinned stand can be expected to produce more *commercial* wood volume (Hoover and Stout 2007). These larger trees can be expected to be more vigorous and will likely be more resistant to fire, drought, insects, and disease (Fettig et al. 2007). Therefore, the carbon stored in trees in a thinned stand may be more likely to stay in the forest and out of the atmosphere for a longer time. Understory thinning, as may be done for restoration of dry forests affected by fire exclusion, may reduce mortality of large old-growth trees and help maintain the carbon stores in those trees (Fellows and Goulden 2008 (in press); Smith, Rizzo, and North 2005).

The carbon effects of thinning are not limited to trees. The effects of thinning treatments on soil respiration are complex and difficult to predict; release of CO_2 from soil may increase, decrease, or remain the same (Kobziar and Stephens 2006; Tang et al. 2005). And thinning typically involves the use of equipment that runs on fossil fuel. A thinning operation can be expected to have the same sources of emissions as more intensive forms of harvest, but lower overall emissions. A full carbon accounting needs to include all of these emissions, as well as the ultimate fate of the material removed in the thinning, but it appears likely that the effects of thinning on carbon balance *per se* will not be decisive. For private landowners, the transition from intensive, short-rotation management based on clear-cutting to less intensive practices may prove financially challenging, but there is some evidence that management based on partial harvest and continuous forest cover can be economical, store more carbon (including that in wood products), and support greater biological diversity (Carey, Lippke, and Sessions 1999; Krankina and Harmon 2006; Perschel, Evans, and Summers 2007).

Fuel-Reduction Treatments, Fire, and Carbon

Throughout the West, various efforts are under way to reduce the density of trees by using thinning and prescribed fire. Motivations for these activities include lowering the risk of uncharacteristically severe fire and associated effects on ecosystems, protecting houses and other human infrastructure from fire, reducing competition among trees for water, and provision of wildlife habitat.

It is commonly assumed, including by many scientists, that these activities (prescribed fire in particular) will also reduce carbon emissions and thus contribute to mitigation strategies (Canadell et al. 2007; Houghton, Hackler, and Lawrence 2000; Krankina and Harmon 2006; Nabuurs et al. 2007). Although this seems intuitively obvious, it is important to bear in mind that fuels-reduction activities also release carbon to the atmosphere: from prescribed fire, disturbance of soil and forest floor during thinning operations, transport and processing of thinned trees, and decay and burning of logging slash and other biomass (whether in the forest or in a biomass plant).

Two basic analyses could help determine how these releases compare to emissions avoided due to reduced fire behavior:

- A complete accounting of carbon emissions associated with thinning (from both the forest and fossil fuels) and prescribed burning, as well as carbon gains—if any—from increased sequestration in treated forests, and emissions avoided due to reduced severity of subsequent fire.

- Quantifying the probabilities that treated and untreated forests will burn during conditions likely to lead to a crown fire (a wildfire spreading in the treetops). That is, even if treatments would successfully reduce fire behavior, what is the likelihood that treated acres would burn in a high-severity wildfire during the time that the treatment would be effective?

The possibility that a treatment may not be adequate to prevent a high-severity (crown) fire, for instance in very extreme weather conditions, would also need to be factored in.

Research is under way to address the carbon accounting for fuels-reduction treatments, and strategies for locating treatments are being refined that should lead to increased likelihood that fuel treatments will influence fire behavior. However, considerable uncertainty remains about both sets of questions. One quantified study in Europe, in the context of the European Union's Kyoto protocols, concluded that emissions from periodic prescribed fires would be less than those of the high-severity wildfires they are intended to prevent, at least in dry, fire-prone forests (Narayan et al. 2007).

In moist forests, where fire is infrequent, carbon-offset credits could be given for forest practices such as extended rotation lengths that are expected to increase carbon stores over time. These credits might be reduced, or insured, based on the probability that the forest could burn and release some of its anticipated carbon stores (Ruddell et al. 2007). In dry, fire-prone forests, if carbon credits were to be based on treatments that will reduce carbon emissions from fire, the value of these avoided emissions would need to be reduced based on the probability that a fire will *not* occur during the period the treatments are effective. Prescribed fire can be used to extend the period of effectiveness of fuels-reduction treatments, thereby increasing the probability that an area will burn less severely if and when a wildfire reaches

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it, thus increasing the probability that the carbon benefits will be achieved. Carbon releases from such maintenance fires would need to be accounted for.

Research in ponderosa pine forests in Arizona suggests that restoration treatments that remove understory trees may provide some carbon benefits, depending on the fate of harvested biomass (Finkral and Evans 2008). Due to lack of available industrial infrastructure for biomass utilization, the wood in this study was used as firewood, and slash was piled and burned in the forest. Accounting for fossil fuel use in logging, transportation, and processing, as well as calculations of avoided emissions due to reduced fire behavior, the project was a net source of CO_2 to the atmosphere. Including below-ground releases (root decay) and prescribed burning of accumulated forest floor (not done in this study, but commonly part of such treatments) would increase the estimated releases (Kaye et al. 2005). The carbon costs (emissions) from slash burning alone were 70 percent greater than the benefits (avoided emissions) expected from reduced fire severity. One option not explicitly examined in this study would be to store wood in long-lived products, and burn slash efficiently in a biomass plant, presumably offsetting fossil fuels that otherwise would have been used for heat or generation of electricity. With the fossil-fuel offset, it appears that the direct effects of such a project could be roughly carbon-neutral. The potential avoided emissions from wildfire would improve the balance. Other researchers (Sisk et al. 2004) calculated an annual probability of fire (larger than 50 acres and of any severity) occurring in the area of 2.8 percent, which, if refined with data on fire severity and combined with an estimate of the length of time the treatment would remain effective (perhaps twenty years), could provide part of the basis for discounting the anticipated benefits of reduced emissions if the area were to burn in a wildfire.[5] The key factor will be *future* fire probabilities, which, as discussed above, are highly likely to continue to increase in the West (Westerling et al. 2006; Bachelet, Lenihan, and Neilson 2007).

Calculating the potential carbon benefits of fuels reduction and the likelihood that treated areas will be affected by fire would be a form of quantified risk assessment for wildfire, an area of active research (Finney 2005). Some simplification will be necessary to come up with calculations that are practical (Finney 2005). However, highly simplified analyses that assume that fires and treatments are randomly located and that don't incorporate the influence of treatments on fire behavior and size (Rhodes and Baker 2008) will give unrealistically low estimates of the probability of fire encountering a treated area during the period the treatment will be effective in influencing fire behavior. Implicitly assuming that every treated area will burn, and burn with reduced severity (Hurteau, Koch, and Hungate 2008), is not realistic either. The scientific basis for strategically locating treatments for optimal influence on fire behavior is being refined, taking into consideration landscape-level characteristics such as forest type and condition, topography, ignition sources, and probable wind direction (Finney et al. 2006; Ager et al. 2007; Hessburg et al. 2007; Miller 2003). However, this is work in progress and there is as yet no consistent guidance to Forest Service managers on how best to identify and prioritize treatments (USDA-OIG 2006). Presumed carbon benefits will need to be reduced, but by how much remains highly uncertain, in part due to the difficulty of predicting future fire regimes. As understanding of optimal landscape-scale strategies improves, and as this understanding is better reflected in policy and management, these discounts can be reduced. In general, treatments strategically located to influence fire behavior and spread, or that protect the greatest biomass (i.e., old growth), may have greater probability of providing net carbon benefits. While further research will be needed, it appears likely that the carbon implications of fuels treatments will be small, one way or the other, and won't be the dominant consideration in deciding whether and how to proceed with such treatments.

Forest Restoration

The inevitability of climate change raises questions about the role and efficacy of forest "restoration," a term that usually implies returning to some past conditions, often interpreted as "presettlement," or around 1850 in the western U.S. The rate and magnitude of climate change that is headed our way, and the changes this will impose on forests and other vegetation, make the notion of returning forests to the structure and composition of 1850 seem more nostalgic than realistic (Harris et al. 2006; Millar and Brubaker 2005). Harris et al. (2006) question whether we should be "focusing on past systems as the target for ecological restoration activities—or should we rather be reinstating the space and capacity for ecosystem functions and processes?" This implies a very different conceptual framework for management of our national forests, and one that has not been thoroughly explored.

The forests' response to climate change will not be immediate, however, nor can they be expected to stabilize any time soon; the discrepancies between the ever-changing "present" and the past will grow over time (Seastedt, Hobbs, and Suding 2008). "In a world of changing climate, structural targets of historical conditions will become progressively less meaningful to ecosystem maintenance" (Keeley and Stephenson 2000). In the near term, managing for something akin to historic composition and structure, adjusted in consideration of current and anticipated conditions, may still be a reasonable objective, but we need to be prepared to continually adjust our expectations in light of changing climatic conditions. The coastal plain of the southeastern U.S. once supported millions of acres of forest and savannas dominated by longleaf pine that have largely been lost to conversion to agriculture and timber as well as fire exclusion (White, Wilds, and Thunhorst 1998). Conservation of biological diversity has been a primary motivation for restoration efforts, but it appears that restoration of longleaf pine can also help create forests that will

5 Winrock International is conducting research, under contract with the West Coast Carbon Sequestration Partnership (WESTCARB) to develop carbon accounting for fuels-reduction projects near Lakeview, Oregon and in Shasta County, California (Martin, Petrova, and Pearson 2007). A final report from Winrock International is due in 2009.

be more resilient to anticipated climate change (increasing temperatures and more drought) and that may, especially with longer rotations, help store more carbon than other forest types (Kush et al. 2004).

Strategies for Conserving Biological Diversity

ALTHOUGH SCIENTISTS HAVE debated what the relationships between biodiversity and resilience are for many years, there appears to be increasing evidence that more biologically diverse systems tend to be more productive (Cardinale et al. 2007) and more resilient—that is, they are more apt to return to previous condition or function following disturbance. Or, perhaps more relevant to the context of climate change and the threats it poses to species, if ecosystems become less biologically diverse, they can be expected to be less productive and less resilient (Carpenter et al. 2001; Elmqvist et al. 2003; Folke et al. 2004; Hooper et al. 2005; Walker, Kinzig, and Langridge 1999). Forests and other terrestrial ecosystems play an important role in storing carbon, thus reducing the potential severity of climate change. Ecosystems with undiminished biodiversity may both store more carbon (if they are more productive) and retain pools of carbon longer in the face of climate change (if they are more resilient). Thus, there should be no inherent conflict between managing for climate change and managing for biological diversity; both objectives need to be pursued. Conservation of biodiversity can be both a mitigation strategy and an adaptation strategy.

Conservation Principles

Despite the many uncertainties related to the conservation of biological diversity in light of climate change, there are some basic conservation principles that can be relied on. As Peters (1992) put it, "One basic truth is that the less populations are reduced by development now, the more resilient they will be in the face of climate change. Thus, sound conservation now, in which we try to conserve more than just the minimum number of individuals of a species necessary for present survival, would be an excellent way to start planning for climate change."

Although climate change can be viewed as an added threat to biodiversity—in addition to loss, degradation, and fragmentation of habitat, invasive species, exploitation, and pollution—it may be more usefully seen as changing the context for all these existing threats or stressors. For instance, habitat fragmentation may have even more serious implications for species that need to relocate to new areas to find suitable habitat under changing climate, or a new suite of exotic species may pose threats as the climate changes and makes new areas suitable for invasion. All too often, even in the absence of climate change, conservation strategies are not sufficient to halt or reverse declines in biodiversity (Lovejoy 2004). Climate change will only make the task of conservation more challenging. These challenges are compounded by the fact that, for the foreseeable future, climate will be in constant flux; developing conservation strategies will be like hitting a moving target (Hannah and Salm 2004), repeatedly.

The basic elements of conservation planning will remain the same: identifying species and habitats of concern, establishing landscape-scale networks that include reserves (protected areas), a matrix that provides connectivity among reserves, and provision for aquatic and other special habitats (Lindenmayer and Franklin 2002).

How and where these elements are applied will likely need to be modified and/or supplemented in light of climate change. Assessments of which species and communities are at risk will need to be revised to take climate change into consideration. The fact that most species will respond individualistically to climate change (Lovejoy 2004; Millar, Stephenson, and Stephens 2007) by moving—if they can—to new locations will challenge our concepts of biological communities and what it means to conserve them. Protected-area plans will need to consider not only current distributions of species but also likely future distributions as they respond to changing climate. Additional protected areas will likely be needed (Peters 1992), as well as connectivity to allow species to move between areas. Protected areas that contain greater diversity of topography and soils and include greater range of elevation will be more likely to continue to provide habitat for species of concern (Peters 1992).

Novel ecosystems (unprecedented combinations of plants, animals, and landscapes) will arise, posing many additional challenges for conservation planners. As Seastedt et al. (2008) observe, "The point is not to think outside the box, but to recognize that the box itself has moved, and in the twenty-first century, will continue to move more and more rapidly." Although reserves will continue to have geographically fixed boundaries, their management can be a flex-


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ible part of a dynamic landscape strategy (Hannah and Hansen 2004). It may be appropriate to think of reserves not as homes for particular species but as arenas for changing species diversity (Halpin 1997), and to ensure persistence of species within large ecoregions, not necessarily at any given historical location (Millar, Stephenson, and Stephens 2007). The potential need to move species around, to assist in their migration to or colonization of newly suitable habitats, will require scientific input and considerable public debate to resolve both practical and ethical questions (McLachlan, Hellmann, and Schwartz 2007; Hunter 2007).

Computer-based models of global climate have been developed by various institutions around the world to gain better understanding of the climate and forecast how it will change with increasing greenhouse gases. The outputs from climate models an be coupled with various models of vegetation growth and distribution to yield predictions of the distribution of plant species or vegetation types, and thus of habitat. The vegetation models may be able to dynamically track changing climate, or be based on presumed new equilibrium climate, and they vary as to the extent to which they include factors such as soils, fire, insects and disease. The range of outputs from these various combinations of models, along with uncertainties about what will happen with human-caused emissions of greenhouse gases, mean that these predictions are currently not directly applicable to local or even regional land-management planning. However, they can provide an indication of the magnitude of possible changes and the likely directions of movement of species and vegetation types. The models are continually being improved, and will be increasingly useful as they are adapted to smaller regions and incorporate more factors influencing the distributions of plants and animals.

It is important to note that the maps produced by these models[6] indicate *potential* distribution, reflecting where suitable combinations of temperature and moisture are likely to occur in the future; they do not necessarily reflect species' ability to move to the newly suitable areas, or whether other factors such as soils may mean that the areas won't provide suitable habitat. Habitat fragmentation can severely restrict species' ability to colonize new habitats otherwise rendered suitable by climate change (Iverson, Prasad, and Schwartz 1999; Iverson, Schwartz, and Prasad 2004). This problem is compounded by the often small and disjunct potential ranges in topographically diverse areas typical of the West (Shafer, Bartlein, and Thompson 2001). Even without barriers to movement, species may not be able to keep up with unprecedented rates of climate change (Solomon and Kirilenko 1997; Neilson et al. 2005), providing opportunities for invasive species that typically have greater abilities to disperse (Simberloff 2000; Hansen et al. 2001; Lovejoy 2004).

Differential abilities to move to, and persist in, newly suitable areas can disconnect species from their habitat either in space or in time. Root and Schneider (1993) provide two illustrative examples involving birds and forest habitats. One is the Kirtland's warbler, the range of which is limited to jack pine forests of northern Michigan. As climate warms, jack pine is expected to migrate northward. Although the Kirtland's warbler could move with the pine forest, the trees' new range would not include the well-drained sandy soils the ground-nesting warbler requires, and the species has been predicted to go extinct in a matter of decades.

An example of a potential temporal disconnect is provided by the red-cockaded woodpecker of the southeastern U.S., which relies on mature and old-growth pine trees (preferentially longleaf pine) for nesting habitat. If extensive areas of mature pine trees die as a result of drought and temperature stress or the invasion of novel insects, the woodpeckers would be threatened by loss of suitable nesting habitat. Even if new pines became established, the

6 Examples of the possible future distribution of tree species, based on these sorts of models, can be found online, for example at a website covering North America maintained by the Canadian Forest Service (http://planthardiness.gc.ca/ph_main.pl?lang=en), and for the eastern United States maintained by the U.S. Forest Service's Northern Research Station (http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html). Shafer (2001) provides maps for many species in the western U.S.

woodpeckers could not survive the many decades required for new trees to mature.

Climate change will entail challenges for many species of wildlife, but the picture is not unrelentingly grim. Some species, in some places and at some times, will benefit from the changes (Hansen et al. 2001). It is worth recalling that existing species, or the evolutionary lineages they represent, have survived some dramatic climate changes in the past (Millar and Brubaker 2005; National Research Council 2002). This knowledge should not be a source of complacency, but it may offer some hope.

Conclusion

WHAT IS CLEAR BEYOND ANY reasonable doubt is that climate change is happening, that its results could be highly disruptive of both human and natural systems, and that effective action can reduce future climate change and its associated risks. Early actions are particularly important, and storage of carbon by forests can provide a significant and timely mechanism for both keeping carbon from *entering* the atmosphere and *removing* carbon from the atmosphere. Strategies to increase carbon storage by forests, including wood products, need to be based on the best available science and, if they are to qualify for carbon offsets, will be expected to meet widely accepted standards for additionality, permanence, and other general criteria.

It is also clear that management strategies that will increase carbon storage in forests—most generally, protecting old-growth forests and increasing the average age of forests at landscape scales by reducing the frequency and severity of disturbance—can provide complementary or synergistic benefits for many other forest values such as biodiversity conservation, recreation, and watershed integrity (Krankina and Harmon 2006; Nabuurs et al. 2007), although increased growth of trees may reduce water quantity (Birdsey et al. 2007). Conversely, logging of existing old-growth forests creates a carbon debt that will not be balanced out by storage in wood products (Krankina and Harmon 2006; Heath and Birdsey 1993). Actions to improve the abundance and genetic diversity of wildlife will increase the likelihood that species will successfully adapt to climate change, and these actions are also more apt to be consistent with strategies to sequester carbon in ecosystems. Maintaining effective soil cover and integrity will help store carbon, buffer against extreme rainfall, and resist the invasion of some invasive plant species.

Among the many uncertainties associated with climate change, one is the human response to the threat. To what extent will we reduce emissions of greenhouse gases, and how quickly? Individual, institutional, and governmental choices will profoundly influence the extent of future climate change, but despite growing awareness of these threats, it is difficult to predict which choices we will make.

As a consequence, it is even more difficult to predict how forest ecosystems will transform or how management should change in anticipation of, or in response to, ecological transformation. We know that forest ecosystems have already been affected by human-caused climate modification, and more changes will surely come over time. It is likely that these changes will enter the realm where abrupt and surprising transitions are virtually certain.

Many debates over forest management continue to focus on how to best describe and achieve historic conditions, even as climate change interacts with other human-caused stresses such as habitat fragmentation, pollution, and invasive species to create conditions that have no historical precedent (Millar, Stephenson, and Stephens 2007). Although interactive climate and vegetation models are being improved steadily and provide useful information about likely changes, they lack sufficient resolution at the local or regional level to provide clear guidance for forest management. And they are limited by the fundamental uncertainty about how effectively we will respond to the threat of climate change. Given limitations on both our knowledge and the resources available to take action, it is likely that the majority of forests will, for better or worse, respond to climate change without human intervention (Spittlehouse 2005).

In the near term, for the next decade or so, many prior management objectives continue to be appropriate. These include improving forest resilience to known stresses such as fire, insects, and drought, where some forms of thinning (including fuels-reduction) may be useful as adaptation strategies, even though their utility as mitigation may be uncertain. Reducing or eliminating stresses such as habitat fragmentation, watershed degradation, and invasive species also appear necessary. General rules on how to manage ever-changing ecosystems are apt to prove elusive. However, actions to improve the abundance and genetic diversity of native species, while increasing functional diversity, will increase the viability of species and ecosystems in the face of the uncertainties of changing climate (Seastedt, Hobbs, and Suding 2008).

As troubling as it may be to contemplate what we do and do not know about forest ecosystems and how they may be affected by climate change, these concerns only multiply when we consider the ability of the Forest Service, Congress, and other institutions to respond to the challenge. We must consider the intersecting combination of social and ecological systems, rather than thinking about ecosystems as abstract and isolated entities (Walker and Salt 2006). Human responses need to be more nimble and innovative (Hannah and Salm 2004), characteristics not typically associated with the federal government. More effective involvement of local knowledge may provide part of the answer (Chapin et al. 2006).

A report by the U.S. Government Accountability Office (GAO 2007) identified multiple problems with how the Forest Service and other resource agencies are addressing (or failing to address) climate change. The challenges include modifying how agencies approach their missions (from focusing on historic conditions to anticipating climate change), improving guidance from Congress and the executive branch, and improving data and computer models. These challenges are only exacerbated by shrinking budgets and staffs. As Seastedt et al. (2008) put it, "There are too many problems confronting too few managers with too few resources."

Even though the effects of climate change are very rapid in ecological terms, they will be slow compared to typical funding and management timelines (Peters and Lovejoy 1992; Chapin et al. 2006). These disconnects in time-scale can be compounded by the fragmented or "stove-piped" approach to natural resource management characteristic of government agencies and many other institutions (Chapin et al. 2006). Greater cross-discipline integration is necessary, as is involvement of scientists in management, particularly in the design of adaptive management approaches, and in education of both managers and interested members of the public (Seastedt, Hobbs, and Suding 2008). Although adaptive management is often viewed as a concept burdened with repeated failure and at risk of being rejected as a "hollow marketing tool," (Bormann, Haynes, and Martin 2007), it is hard to imagine that we will succeed in dealing with climate change unless we succeed in putting the principles of adaptive management—by whatever name—to work. The administration and agencies will need to support and promote adaptive management, Congress will need to fund it, scientists must be engaged in it, and everyone who cares about national forests will need to be part of figuring out how to make it work (Stankey, Clark, and Bormann 2005).

Connie Millar, a scientist with the Sierra Nevada Research Center of the Forest Service's Pacific Southwest Research Station, has, in a series of papers[7] and with a variety of coauthors, developed and refined a multipart strategic framework for addressing climate change. Some key elements of this strategy include helping ecosystems to resist climate change (generally a limited, short-term approach), to be more resilient to climate change and associated disturbances, or be more able to respond without rapid threshold or catastrophic change (Millar, Stephenson, and Stephens 2007). Given the magnitude and rate of change we face and the limited resources that are available to deal with them, Millar et al. (2007) also recommend a triage-like approach for selecting priorities, at least in the short term.

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There is no question that strategies for addressing climate change, whether focused on mitigation or adaptation, entail substantial uncertainties and risks. Yet the uncertainties and risks of inaction are just as great. We need to take actions that we are confident need to occur, such as encouraging greater sequestration of carbon, restoring resilience to fire-prone ecosystems, recovering populations of at-risk species, and reducing barriers to species movement. Not every perceived problem requires immediate action, however, and it will be crucial that we prepare to act, in part by adjusting our thinking and our expectations, so that we can proceed with greater knowledge and confidence in the future.

Millar et al. (2007) state that one goal of their paper is to engage dialogue on the issue of management responses to climate change. Everyone who cares about the fate of our national forests needs to become better informed and more engaged in the conversation that scientists such as Millar can help to facilitate. I hope this paper is a useful contribution to that conversation.

7 Available at http: //www.fs.fed.us/psw/programs/snrc/staff/millar/

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R. FIELDS

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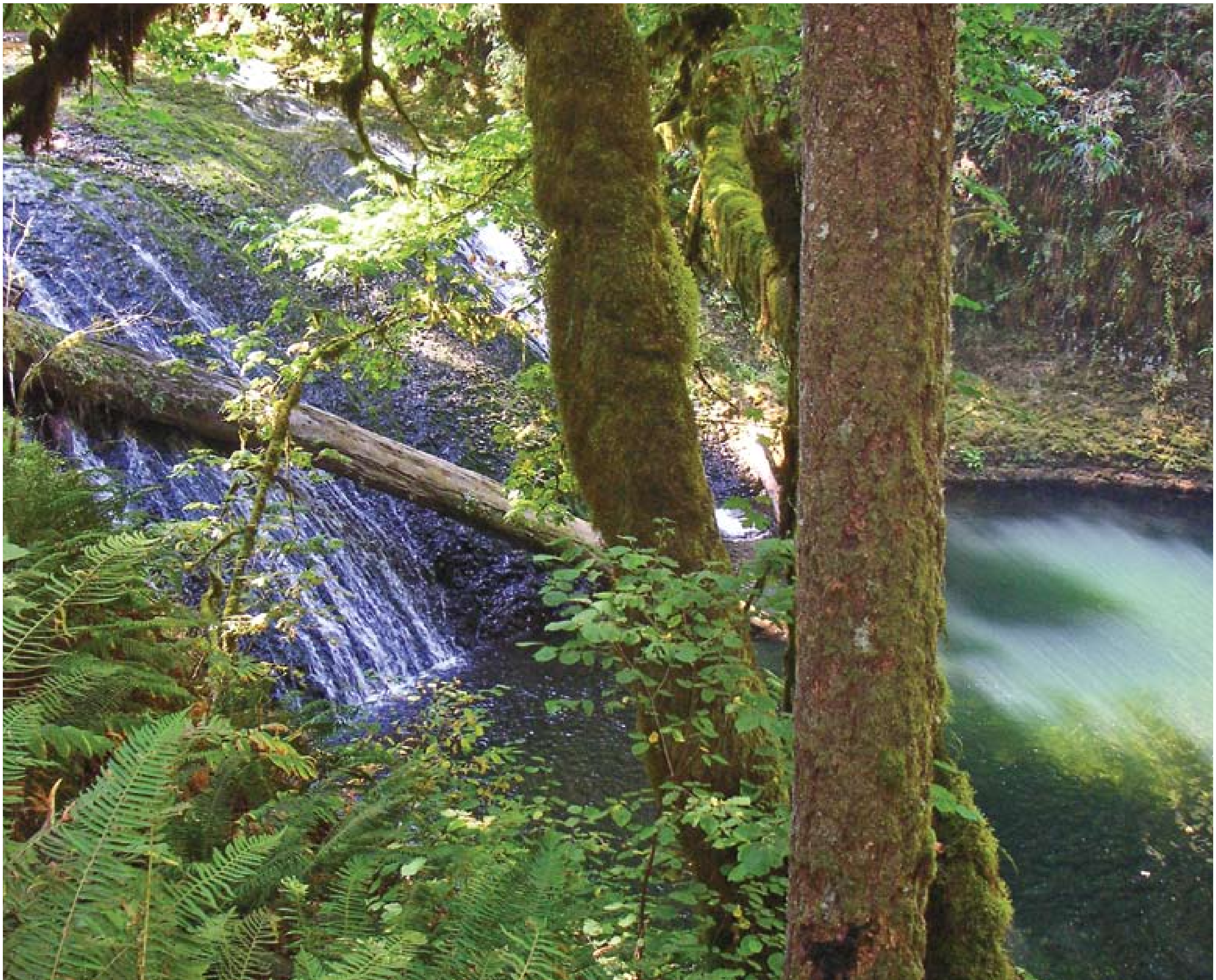

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