Silvicultural Challenges and Options in the Context of Global Change: "Simple" Fixes and Opportunities for New Management Approaches

Klaus J. Puettmann

ABSTRACT

A major challenge for foresters in the future will be issues related to global change. Global change expresses itself in a variety of ways, depending on regional vegetation and climate patterns, small-scale topographic differences, tree species, and stand development stages. Using silviculture as an example, the variety of steps linking global change—as a general concept—and actual management decisions is explored. The first task is to relate global change aspects to silviculturally relevant scales. Second, silvicultural responses must reflect the wide variety of changes, including their interactions. A number of management recommendations have been proposed from the global scale to the application of specific silvicultural treatments. These recommendations are mostly focused on increasing the resistance of forests to perturbations. Increasing ecosystem adaptability and resilience through silvicultural practices may benefit from developments in other scientific fields. Recent advances in the complexity and ecosystem sciences may provide approaches that are better suited for a future with increased variability and uncertainty in ecological and social conditions. Specifically, managing forests as complex adaptive systems may provide a conceptual framework that can be useful for silviculture, even though much work still must be done to fully explore the implications of such a new framework for silvicultural decisionmaking.

Keywords: silviculture, global change, climate change, invasive species, resilience, adaptability, complex adaptive systems

Global Change and Uncertainty

Forest managers must deal with numerous developments that can be summarized under the umbrella term "global change." Because many of these developments may result in increased variability and uncertainty regarding future environmental, biological, and social conditions, they provide new challenges for silviculture. In terms of environmental conditions, climate change with predicted increases in temperatures and changes in precipitation patterns may result in more variation in climate and weather patterns. An increased frequency of extreme weather events is expected to lead to an associated shift in disturbance regimes (Dale et al. 2001). Increased variability and uncertainty of biological conditions are, e.g., the result of growing global trade and travel and the associated increase in the likelihood of introducing new species (Haack 2006), which may also benefit from climate change (Walther 2003). In particular, invasive insects or diseases can result in rapid changes in species composition and ecosystem structures and functions (e.g., Anagnostakis 1987, Poland and McCullough 2006). Social developments, including new environmental and trade policies (Perez-Garcia et al. 2002), will provide new and unexpected marketing challenges and opportunities for wood and other forest products (Shanley et al. 2002, Ragauskas et al. 2006). At the same time, silvicultural investments are now harder to justify, because of reduced budgets for public landholding agencies and higher economic expectations of private investors.

These trends suggest that forest ecosystems are likely to experience large changes in their structural and functional attributes. Additionally, there will be different social

Received May 21, 2010; accepted December 2, 2010.

Klaus J. Puettmann (klaus.puettmann@oregonstate.edu) is Edmund Hayes Professor in Silviculture Alternatives, Oregon State University, Forest Science, 321 Richardson Hall, Corvallis, OR 97331. *The author acknowledges his colleagues and students for interesting discussions and feedback, especially C. Messier, D. Coates, A. Ares, and D. Hibbs. Caryn Davis and Bryan Bernart helped with editorial issues and figures. Two reviewers greatly improved the article. Work on this article was supported by the Edmund Hayes Professorship at Oregon State University.*

Global changes are changes in the global environment (including alterations in climate, land productivity, oceans and other water resources, atmospheric chemistry, and ecological systems) that may alter the capacity of the Earth to sustain life (from the Global Change Research Act of 1990).

Complex adaptive systems contain a population of diverse agents, all of which are connected, with behaviors and actions that are interdependent and that exhibit adaptation or self-organization (based on S. Page, The Great Courses, U Michigan).

Engineering resilience is defined as the rate at which a system returns to a single steady or cyclic state following a perturbation. **Ecological resilience** is the response to change in a way that sustains fundamental functions, structure, identity, and feedback (based on Petersen et al. 1998).

Ecosystem service resilience is the ability of an ecosystem to provide the desired ecosystem goods and services (based on Folke et al. 2002, Brand and Jax 2007).

demands and expectations placed on these ecosystems than in the past. Ecosystems may even be altered to a degree that does not have a historical equivalent, which qualifies them as "no-analog systems" (sensu Seastedt et al. 2008). This threshold is important because many silvicultural practices are based on past experiences or on the historical range of natural variability (Smith et al. 1997, Bergeron et al. 1999, Nyland 2002). In no-analog ecosystems, the record of historical conditions cannot provide a straightforward guide for future management goals and practices, not even in the case of parks and wilderness areas (Hobbs et al. 2010). Instead, such historical insights may only enhance our understanding of specific processes or interactions. Consequently, future silvicultural practices can not rely solely on our understanding of ecological relationships derived from past experience.

Managing ecosystems under new environmental, social, and economic conditions may therefore benefit from new and although unproven practices and approaches (Bolte et al. 2009, Puettmann et al. 2009). Seastedt et al. (2008) suggest that the panarchy model (Gunderson and Holling 2002, Drever et al. 2006) may be useful in the development of management approaches that address this issue. The panarchy model is essentially a hypothesis that suggests that disturbances and associated reassemblies are crucial components that drive ecosystems' ability to adapt to new environmental conditions. Puettmann et al. (2009) go one step further and suggest that future management concepts should be based on complexity science, i.e., managing forests as complex adaptive systems. Both of these approaches are related to and focus on the concepts of adaptability and resilience in ecosystems. They are an extension of the long-standing discussion in the ecological community regarding whether or not increased biodiversity (mostly assessed as species diversity) leads to ecosystem stability (e.g., Ives and Carpenter 2007). In light of global change issues, silviculturists can learn and contribute a great deal by participating in the dialogue around ecosystem adaptability and resilience.

The following section first highlights the variety of aspects involved in "global change" and the need to make this generic term "operational" before it can provide a basis for silvicultural decisionmaking. Next, I briefly describe several options that have been proposed to deal with implications of global change. The third section provides a brief description of advancement in theories and concepts from the ecosystem and complexity sciences that may benefit silviculturists in their search for a response to global change. The final section details the ways in which silvicultural practices could be modified to accommodate global change, with a special emphasis on how managing forests as complex adaptive systems may be incorporated into silvicultural decisionmaking.

The Diversity of Global Change

"Global change" has become an ever present buzzword (more than 123 million hits on Google.com). As a concept, it covers a full suite of changes in the global environment (see sidebar). The large scale of this concept contrasts with the relatively small tree-, stand-, and landscape scales that are typically the basis for silvicultural decisionmaking. Making the concept of global change useful for silviculture requires a more detailed look at how global change is expressed at silviculturally relevant scales. Any discussion of the impact of global change on forest management must acknowledge that it may directly affect plants by altering their physiological processes or resource levels. Alternatively, altered disturbance regimes are examples of the indirect impact of global change. Furthermore, forest ecosystems do not react to global change as an entity. Every species will respond differently and, at least partially, independently to changes in its environment, thus altering a given ecosystem's processes and functions. This section provides examples of the diversity of scales and aspects that must be considered when developing silvicultural practices that respond to or deal with global change. The following discussion focuses on climate issues because of its prevalence in the literature. Other aspects, such as those regarding atmospheric chemistry or the invasion of exotic plants and diseases, must be evaluated and assessed in a similar context.

A major challenge facing silviculturists is the uncertainty associated with various aspects of global change. For example, more than 23 general circulation models are currently in use to predict climatic changes. Furthermore, much is unknown regarding how ecosystems respond to climate change and other perturbations. Even more uncertainty exists regarding forest ecosystems' responses to silvicultural manipulations under altered conditions (Lawler et al. 2010), especially because the rates of change may be quite a bit faster than a forest's response to manipulations. Additionally, there is no single source of information about the prediction of global change and the uncertainties associated with it. This makes it difficult for silviculturists to operationally assess what specific challenges and uncertainties they should expect in the coming years.

Climate models predict that global mean temperature will increase from 1.8 to 4°C by the end of this century (Intergovernmental Panel on Climate Change [IPCC] 2007). However, general circulation models and research results show a hierarchy of impacts. For example, climate change impacts vary across, but also within, regions (IPCC 2007). The sensitivity of an area to climate change is influenced by a variety of factors, including its adjacency to an ocean and ocean currents and its proximity to mountainous terrain or larger wind patterns (e.g., Mote et al. 2003, Lindner et al. 2007). At the same time, smaller-scale differences are also likely to influence changes in climatic conditions. For example, in mountainous terrain, temperature regimes on upper slopes and ridgelines are closely related to larger-scale circulation patterns. In contrast, temperature regimes in valley bottoms and cold air drainages are predicted to be relatively independent of changes in regional circulation patterns (Daly et al. 2009), which suggests that climate change impacts will vary across watershed scales and even within stand scales.

Not all tree species, and thus forest types, are similarly affected by changes in temperature and moisture regimes. Some simulation studies suggest that global change will provide an improvement in growing conditions for trees (e.g., Nabuurs et al. 2002). Climate envelope models suggest that species differ in the breadth of their temperature and moisture niches and thus their ability to withstand changes in climate regimes (McKenney et al. 2007), especially in situations involving extreme weather events (Zimmermann et al. 2009). For example, under climate change scenarios and dispersal assumptions, changes in the climate envelopes of tree species in the United States ranged from a 44% increase to a 94% decrease in expected species ranges. The responses showed distinct regional patterns. Tree species from the Southeast appear less sensitive to climate change than do species from other regions in the United States (McKenney et al. 2007). Changes in environmental and biological conditions are likely more obvious in areas near the edges of a species' distribution but will also impact areas in the central portion of the distribution (Griesbauer and Green 2010). A general consensus appears to be the special concern regarding areas where species grow at a moisture-limited range of conditions.

Similarly, not all stages of tree and stand development have the same sensitivity to changes in climate. The specific impact through changes in moisture regimes or wind, snow, and fire disturbance will determine the stage of stand development most heavily affected. For example, the regeneration phase (sensu Oliver and Larson 1996) appears to be quite sensitive to changes in climate. Small changes in temperature and moisture regimes can lead to problems in chilling requirements for seed germination (Kimmins and Lavender 1992) and for the survival of germinants (Küssner 2003). On the other hand, during most of typical rotation period, trees are less sensitive to weather patterns and associated disturbance regimes (Franklin et al. 1987, Spiecker et al. 1997).

Finally, none of the components of global change act in isolation. Impacts of other aspects of global change, such as invasive species or diseases, may be magnified or tempered by changes in climate regimes (Walther 2003). The discussion regarding the diversity in interactions of factors and scales points out that there is no single, coherent, "global change," and that being informed about emerging issues that affect local management concerns is a major challenge for silviculturists (Stephens et al. 2010). In conjunction with other aspects, including changes in social, political, and economic settings, the variety of future management challenges also suggest that there can be no simple general recommendations or widely applicable silvicultural response to global change.

Silviculture Recommendations at a Hierarchy of Scales

Foresters have a long tradition of adapting practices to changing social, ecological, and economic conditions (Puettmann et al. 2009), and global change issues are no exception. Much of the silvicultural response to global change factors, such as the influx of invasive species, has been locally developed and implemented. By contrast, a wide array of recommendations have been proposed that cover a hierarchy of factors, from global scales, to forests, farmlands, and other ecosystems, to recommendations of specific silvicultural treatments.

Global assessments, such as the IPPC Fourth Assessment Report (IPCC 2007) cover a wide array of issues, including water, food, and fiber resources; human health; and impacts of climate change on industry, settlement, and society. The report includes mitigation strategies for various industries and fields, including the forestry sector, but most of those are focused on forest policy. On a national scale, the US Climate Change Science Program (CCSP) Report (CCSP 2009) provided general recommendations for a national program addressing climate change issues. Their recommendations covered all ecosystems in the United States and included general aspects, such as increased research and monitoring efforts and the instigation of institutional changes. The report suggests increasing the adaptive capacity of ecosystems, but does not provide any specific treatments at silvicultural relevant scales. National reports that specifically focus on forests, such as those by the Society of American Foresters Climate Change and Carbon Sequestration Task Force (Malmsheimer et al. 2008), cover larger-scale aspects, such as preventing and reducing greenhouse gases, forest carbon offset projects, wood and biomass substitution, and wildlife behavior modification.

Several publications focus specifically on silvicultural recommendations. Similar to the aforementioned reports, climate change, rather than global change issues, has received most of the attention. Most silvicultural recommendations are based on the assumption that climate change acts as a stressor. Thus, suggestions for silvicultural approaches have focused on treatments designed to increase tree vigor (e.g., Spittlehouse and Stewart 2003, Anderson 2008, Hemery 2008). Table 1 provides a list of proposed silvicultural practices that did just this (adapted from Spittlehouse and Stewart 2003, Anderson 2008, and Hemery 2008). There are emerging concerns, however, that global change may alter environmental conditions such that these practices may need to be modified to be effective in dealing with future changes (Bolte et al. 2009).

A consistent theme in the literature is the recommendation for applying a diverse set of silvicultural prescriptions (Spittlehouse and Stewart 2003, Anderson 2008, Hemery 2008, Campbell et al. 2009) with a goal of creating a diversity of stand conditions, ranging from even-aged monocultures at various developmental stages to multiage species mixtures. Other common suggestions include applying silvicultural treatments at a variety of spatial and temporal scales (see Figure 1a in Seymour et al. 2002 and the following discussion). These recommendations are based on the insurance hypothesis (sensu Yachi and Loreau 1999). The resulting diversity of species and vegetation conditions essentially insures that at least a subset of the managed forests will not be affected extensively by global change. By simply spreading the risk through a diversity of silvicultural practices and subsequent stand conditions, silviculturists hope to increase the likelihood that some stands will continue to provide desired ecosystems services under global change conditions. However, at the same time, the likelihood that other stands will be even more negatively affected by global change and not be able to provide such services increases as well. Thus, although the approach of diversifying silvicultural treatments is very attractive and seems intuitive, any insurance comes at a cost. Rather than focusing on diversification per se, the following sections provide ideas detailing how a focus on diversity can be tailored to increase the likelihood of the con-

Table 1. List of silvicultural practices as suggested in response to climate change or other global change factors.

Silvicultural practice	Goal
Thinning or removal of stressed or "susceptible" trees or species	Maintain vigorous trees by providing more resources to remaining vegetation
Remove damaged or highly susceptible trees or species	Remove "infection" centers to reduce susceptibility to pests, droughts, and more
Facilitate seed migration, plant seedlings adapted to predicted future environment	Ensure propagules are adapted to future climate conditions or more stressful environments
Underplant (thinned) stands	Shift genetic composition to better adapted seedlings; provide tree cover in case of overstory mortality
Establish mixed species or multiprovenance forest	Decrease risk of damage due to pest outbreaks; provide greater genetic diversity
Reduce rotation ages	Increase flexibility to alter species or management options
Leave vegetative buffers	Protect unique habitat features, e.g., riparian areas or wetlands
Variable-density plantings or thinnings	Increase spatial variability in growing conditions and habitat
Green tree and snag retention (legacies)	Provide lifeboating, structural enrichment; enhance dispersal, connectivity

Adapted from Spittlehouse and Stewart 2003, Anderson 2008, and Hemery 2008.

tinuous provision of ecosystem goods and services under the wide variety of perturbations expected under global change.

The Management of No-Analog Ecosystems Requires No-Analog Silvicultural Approaches: Managing Forests as Complex Adaptive Systems

If future forest ecosystems do not have a historical equivalent (i.e., are no analog, sensu Seastead et al. 2008), it may be necessary to look for novel (no-analog) approaches to silviculture and forest management. Puettmann et al. (2009) suggest that adapting concepts and theories from the complexity sciences and resiliency theories may be especially timely in the context of global change. In the following section, I will provide a brief overview of complex adaptive systems and resilience theory, first attempts to quantify these concepts, and how these concepts relate to current management approaches.

The novel approach to managing forest ecosystems is based on the observation that forest ecosystems appear to be prime examples of complex adaptive systems (Levin 1998; see sidebar) and that viewing forests as complex adaptive systems can provide insights that are particularly relevant in times of global change (Puettmann et al. 2009). The approach takes advantage of research and experience obtained through complexity science, which became popular in physics (for a detailed history, see the study by Waldrop 1992), and has been applied successfully within other disciplines, such as economics, transportation, climatology, and neurology (Delic and Dum 2006). Complex adaptive systems are more than just complicated, variable, or heterogeneous. Complex adaptive systems consist of a diversity of agents that interact at local levels and across a variety of hierarchical scales (Figure 1). These interactions include nonlinear relationships and positive and negative feedback loops, which at higher scales lead to emergent properties (i.e., properties that cannot be predicted from information about the individual components). Important features of complex adaptive systems include the inherent dynamics, i.e., stable states or equilibriums are the exception, rather than the rule. Another important feature is the bottom-up, decentralized control: the multitude of agents and interactions at low-level local scales are the drivers of ecosystem behavior and are thus critical for the ecosystem's ability to self-organize (i.e., to adapt to changing conditions). This implies that ecosystem responses to perturbations are determined by the rules governing these local interactions. Consequently, perturbations and management practices have to be viewed within the context of whether they can influence these rules and, if so, whether they increase or decrease the adaptability of ecosystems.

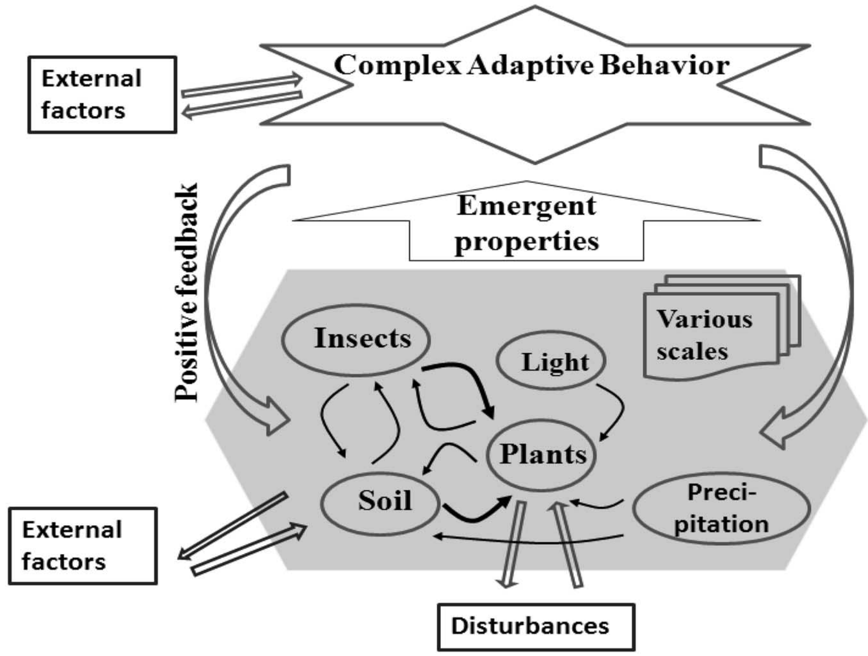

Figure 1. Simplified diagram depicting forests as complex adaptive systems (modified from Wikipedia.com). Low-level interactions include nonlinear relationships and positive and negative feedback loops, which, at higher scales, lead to emergent properties. Ecosystem behavior, including responses to global change, is meditated by the bottom-up, decentralized control, i.e., the multitude of agents and interactions at low-level local scales.

A consequence of nonlinear interactions within and across scales and emergent properties is the inherent unpredictability of the behavior of complex adaptive systems. Such interactions can result in threshold patterns where small changes result in large events (CCSP 2009, Brock and Carpenter

2010). Alternatively, the interactions can act as buffers and the system may be able to withstand substantial perturbations. The interplay between the system's ability to adapt and its ability to withstand changes and perturbations provides opportunities for silvicultural management. These new concepts, especially those associated with efforts to understand and manage ecosystem resilience (e.g., Gunderson and Holling 2002, Drever et al. 2006), have recently gained attention in ecological (e.g., Levin 1998) and socio-ecological sciences (Allen et al. 2003; see also the bibliographic database of the Resilience Alliance 2011). They have gained less attention in forestry, however, and their implications for silvicultural decisions are not yet fully understood (Puettmann et al. 2009).

Ecosystem resilience is a theoretical concept that needs to be "tailored" to be operationally useful for silviculturists. Since its inception, resilience has been defined in numerous ways, reflecting different disciplines and criteria (see sidebar; Holling 1996: for an overview of definitions see Brand and Jax 2007). Because the goals of silviculture are defined by ownership objectives, resilience in managed forests is best defined operationally as the ability to efficiently provide desired ecosystem goods and services (Folke et al. 2002, Brand and Jax 2007). This definition not only allows management flexibility, but also allows for the natural adaptation of ecosystems to new conditions, as long as ecosystem services are provided. Following this definition of resilience, Figure 2 provides a comparison of two silvicultural approaches and their ability to provide desired goods and services under increasing future variability and uncertainty. "Traditional" silviculture has focused on efficiently providing ecosystem services (single or in combination), such as timber, clean water, or wildlife habitat. This approach has often been very successful when ecological, social, and economical conditions were more or less constant or predictable and ample opportunities for intensive silvicultural manipulations existed (e.g., Wagner et al. 2006). By contrast, managing forests as complex adaptive systems shifts the emphasis of silvicultural manipulations away from direct aspects of productivity and toward resilience and the facilitation of the ecosystems' ability to adapt, i.e., respond to a wide variety of changes in conditions. At low variability and uncertainty, such an approach likely leads to lower productivity. As future variability and uncertainty increase, as has been predicted under global change, the increased emphasis on adaption will become more important. The likelihood that desired ecosystem goods and services will be provided under the wide variety of possible future conditions will eventually lead to higher productivity than "traditional" silviculture can provide. In other words, emphasizing adaptability and resilience implies that silviculturists accept a tradeoff. A reduction in the current production of ecosystem goods and services will result in a higher probability of continued production of these goods and services under a wide variety of future conditions. Also, the focus on the ecosystem's ability to adapt to perturbations reduces its reliance on management practices that are currently used to counteract such disturbances, e.g., fertilization and pest-control treatments. Thus, the confidence of silviculturists regarding whether or not they will be able to afford and implement such practices in the future is another factor that must be considered when comparing these management approaches.

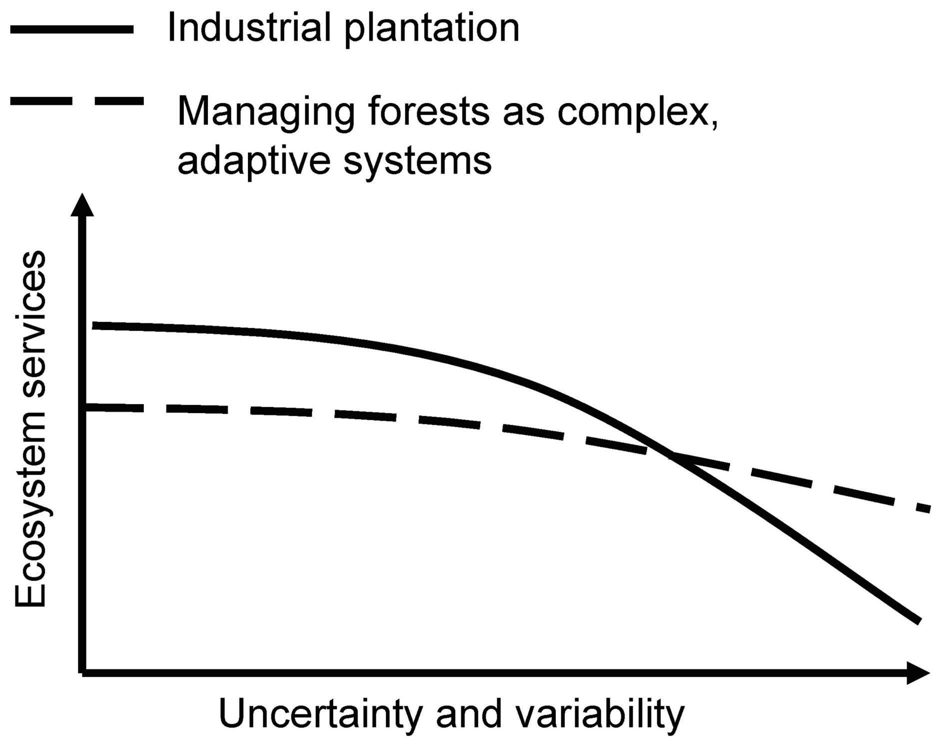

Figure 2. The provision of ecosystem goods and services as related to the degree of future uncertainty and variability. The figure uses timber production in industrial plantations versus managing forests as complex adaptive systems as examples. With increased variability, the level of services a forest can provide is bound to decline as uncertainty and variability increase. Managing forests as complex adaptive systems may lead to lower productivity than industrial plantations during stable and predictable conditions. However, as uncertainty and variability increase, focusing forest management on the adaptive capacity of ecosystems will likely result in higher production of ecosystem goods and services than would typical industrial plantation management strategies.

A major challenge in shifting the focus of management activities from an efficiency paradigm to a focus on adaptability and resilience is that these concepts are not easily quantified (Parrott 2010). Much work remains to be done on this subject, but recent advancements have begun to provide potentially useful measures that go beyond the call for increased diversity (in the broadest sense). For brevity, I will highlight only two approaches. The focus on diversity at spatial and temporal scales provides an example of recent advancements (Peterson et al. 1998, Seymour et al. 2002). Important ecosystem functions and processes, such as herbivory, act on various spatial scales to allow for overlap of functions by avoiding intense competition through spatial separations. In turn, disturbances or changes act at distinct scales; thus, any change will primarily influence functions and processes at their respective scales (see also Seymour et al. 2002). To judge their impact on adaptability and resilience, silvicultural practices can be quantified in terms of their impact on the range of spatial and temporal scales at which ecosystem processes are acting (e.g., Coates and Burton 1997, Cissel et al. 1999). This allows for an assessment of whether such practices increase or decrease the adaptability and resilience of an ecosystem to different perturbations.

The second approach to quantifying adaptability and resilience is based on a shift from focusing on diversity of species, life-form groups, and stand structures to a more mechanistic view by focusing on plant traits as they relate to ecosystems processes (Norberg and Cumming 2008). Reflecting the operational ecosystem service–based definition (resilience "of what . . . to what," sensu Carpenter et al. 2001), traits are sorted by those that contribute to ecosystem functions ("resilience of what") and are quantified as functional types (upper level in Figure 3). Alternatively, traits that relate to an ecosystem's ability to respond to changes ("resilience to what") are quantified as response types (middle level in Figure 3; Norberg and Cumming 2008). Linking the response types to potential perturbations allows a quantitative assessment of the sensitivity of various ecosystem functions to change agents (lower level in Figure 3). Quantifying response-type diversities for the various ecosystem functions will also allow an assessment of whether silvicultural treatments increase or decrease the resilience of these functions to associated changes, such as changes in drought, wind, fire, or temperatures. For example, the cover of forage-producing plants may increase after thinning (e.g., from 30 to 60%) and most of this change (e.g., 40% of the increase) may be caused by the expansion of species that are drought tolerant. The conclusion of such an analysis would be that thinning increased the likelihood that the forest can provide forage under more intensive drought conditions. At the same time, such an analysis may provide guidance on how best to modify silvicultural practices to increase their positive impact on ecosystem resilience. For example, results may suggest that thinning operations are designed specifically to protect plants with desired response types, such as drought tolerance. Much work must be done to make these and other approaches that quantify adaptability and resilience operational (e.g., Carpenter and Brock 2006), but initial efforts appear promising (e.g., Ares et al. 2010).

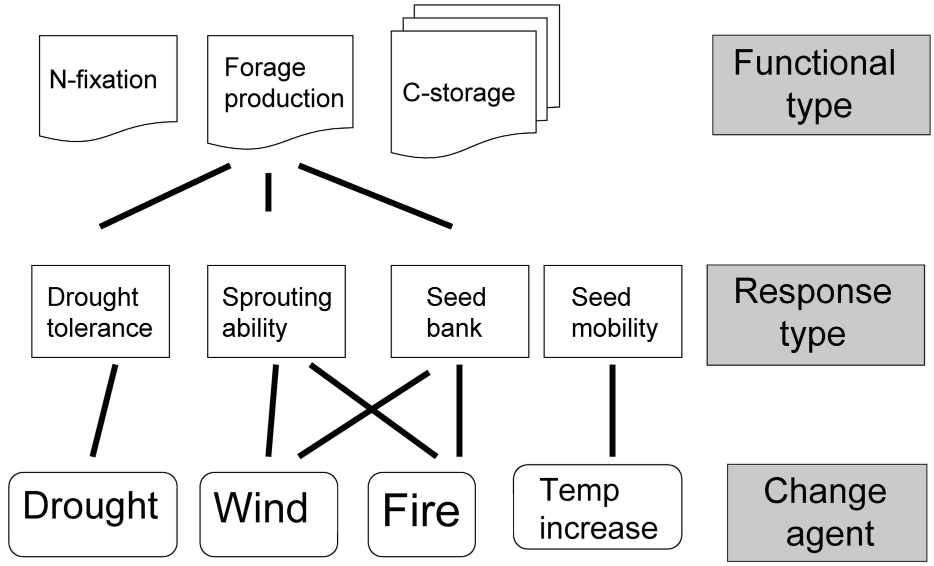

Figure 3. Conceptual model to facilitate quantification of resilience by separating species' traits into those that influence specific ecosystem functions (upper level) and those that reflect a plant's—and thus an ecosystem's—ability to respond to disturbances (middle level). Such separation allows an assessment of which functions are more or less resilient to selected disturbances or perturbations (lower level). Lines provide an example of the resilience of forage production to drought, wind, fire, and temperature increases (see numeric example in text).

Many recent (and not so recent) developments in silviculture have been focused on heterogeneity and diversity and, as such, have been suggested as approaches to dealing with global change issues (e.g., Schütz 2009). Most of these developments were initiated in response to changes in public perception of forests or concerns about environmental consequences stemming from the intensive industrial plantation approach (see the study by Paquette and Messier 2009). The various approaches that can be grouped under the close-to-nature (e.g., Jakobsen 2001) and the ecosystem management labels (e.g., Kohm and Franklin 1997), as well as work that focuses on natural disturbance regimes (e.g., Bergeron et al. 1999) are prominent examples of such developments. Compared with intensive industrial plantations, all of these approaches have an increased emphasis on diversity regarding spatial scales, species mixtures, and heterogeneous stand structures. Their management goals and criteria reflect the local conditions that instigated the search for alternatives to intensively managed plantations and cover a wide range of goals, including ensuring continuous forest cover (Jakobsen 2001, Schmidt 2009); maintaining a diversity of wildlife habitat, especially at larger scales (Kohm and Franklin 1997); and emulating landscape and stand structures as found under natural unmanaged conditions (e.g., Bergeron et al. 1999). At the same time, opportunities to increase heterogeneity in plantations have received more attention (Paquette and Messier 2009).

Managing forests as complex adaptive systems can provide an overarching framework that may be useful to further conceptual development of the approaches listed previously (Figure 4). The practice of managing forests as complex adaptive systems is based on concepts and theories from a variety of scientific fields and thus is not mired by any local heritage. It establishes adaptability and resilience as general criteria for evaluating management practices. These criteria bridge the various aspects important for the different management approaches described previously, such as the spatial scale and continuities of stand structures, species and wildlife habitat diversity, and natural disturbance regimes. Thus, rather than replacing any management approach, complex adaptive systems theory can help further these approaches and make them more useful, especially in the context of the changes and uncertainties associated with global change. On the other hand, the practical experience of silviculturists with industrial plantations, close-to-nature, ecosystem management, and disturbance-based approaches may help make managing forests as complex adaptive systems "operational."

The question of how to manage a forest (and train silviculturists) for adaptability and resilience provides unique challenges for research, education, and management. A logical start is to investigate how ecosystems have historically adapted to changes in climate or other conditions. The panarchy cycle has been suggested as a useful concept in understanding natural adaptations (for more information, see the study by Gunderson and Holling 2002 and Drever et al. 2006). It emphasizes disturbances and associated reassembly phases in terms of their importance for an ecosystem's ability to adapt to new conditions. On the other hand, the successional development or the stand dynamics stages (as described by, e.g., Oliver and Larson 1996), which have received a lot of attention in silviculture teaching and applications (e.g., Smith et al. 1997), are less dynamic and influential in this context. If release and reassembly phases are an integral and necessary part of maintaining and increasing the adaptive ability of ecosystems, they deserve more attention when designing silvicultural prescriptions than they have typically been given in the past (Smith et al. 1997, Nyland 2002). The next section will provide several examples of how this could be accomplished.

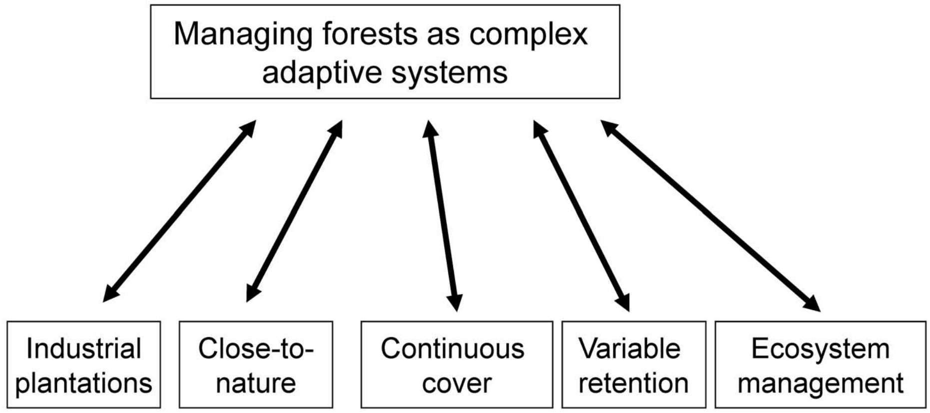

Figure 4. Schematic depicting the interactions between established silvicultural approaches and managing forests as complex adaptive systems. Rather than replacing any established approach, managing forests as complex adaptive systems provides a conceptual framework that will facilitate further development of the established systems. On the other hand, the practical experience gained from the implementation of established systems will help make the theories and concepts derived from complexity science "operational."

How Would Silvicultural Decisions and Practices Differ?

The previous arguments about current recommendations and the application of new concepts in silviculture suggest that two aspects of implementing silvicultural practices deserve discussion in this context. First, silvicultural practices, such as presented in Table 1, may need to be modified to accommodate new, no-analog conditions (Bolte et al. 2009). Second, to facilitate an ecosystem's ability to adapt to new conditions, silviculturists may need to expand their decision criteria when choosing and implementing practices (Puettmann et al. 2009). Both will be discussed later.

As an example of the first point—the need to modify current practices—the recommendations for increased thinning activities in response to concerns about global change are based on the understanding that reducing stand density increases water and other resources available to the residual trees (McDowell et al. 2003, Sala et al. 2005). This, in turn, results in increased tree vigor and thus higher ability to resist and recover from drought (McDowell et al. 2006) and damage from insects, diseases, and other agents (Wallin et al. 2004). However, density management guidelines are based on our current understanding of the balance between competitive relationships and other plant interactions (e.g., Drew and Flewelling 1979, Pretzsch et al. 2002), which may or may not require revision if global change results in different moisture regime and insect and disease patterns. In the same light, the management of overstory layers in shelterwoods is focused on the balance between the facilitation and competition processes necessary to provide optimal conditions for tree regeneration. Overstory densities may be determined by the seedlings' inability to withstand extremely high (Childs and Flint 1987) or low temperatures (Langvall and Orlander 2001) while at the same time ensuring sufficient light, moisture, and nutrients for the seedlings to grow. Depending on the specific impact of global change, the need for facilitation may increase, e.g., higher overstory densities may be necessary to protect seedlings from climate extremes. Alternatively, and maybe even at the same time, climate change may result in lower water availability, which suggests using lower overstory densities to decrease competition for moisture.

In a similar context, the choice of species mixtures may also require a reassessment. As resource and environmental conditions change, the relative importance of competition and facilitation among species may change as well (Forrester et al. 2005). For example, the role of nitrogen fixation as a facilitative process may change if soil nitrogen levels increase because of higher atmospheric nitrogen deposition (Binkley 1983). Also, lower rainfall levels may increase the intensity and importance of competition for water and require adjustments in species mixtures, densities, or spatial arrangements (Stephens et al. 2010).

Reforesting with local or locally adapted seed sources has been a long-standing practice in silviculture (Nyland 2002) and is of special interest in many silvicultural approaches, such as "close-to-nature" silviculture (Jakobsen 2001, Schütz 2009). However, its attractiveness changes in light of concerns that locally adapted seed sources may not be suitable for future conditions (Brange et al. 2008). For example, chilling requirements of the seed may not be fulfilled (Kimmins and Lavender 1992) or physiological processes, such as bud breaks, may no longer be synchronized with the timing of growing seasons (Aitken et al. 2008). If extreme weather events, rather than average conditions, determine the success of management efforts (Smit et al. 1999, Zimmermann et al. 2009), genetic guidelines for seed movements should be reassessed. For species with small populations, fragmented distributions, low fecundity, and low seed and pollen dispersal rates, facilitated migration through seed or seedling movements may be necessary to ensure future presence of tree species in the landscape (Aitken et al. 2008). New guidelines may suggest a diversity of seed from local and adjacent seed zones (St. Clair and Howe 2009) and may even blend the distinction between native and introduced species (Brange et al. 2008).

In contrast to "simple" modifications of current practices, managing forests as complex adaptive systems suggests a shift in viewpoint, which can be integrated into the decision criteria for silvicultural prescriptions (Puettmann 2009). Tying silvicultural practices to new theories and concepts from ecosystem and complexity sciences may be best simplified as "emphasizing how silvicultural practices can increase the ecosystems ability to respond to likely and unexpected changes in future conditions." For example, thinning prescriptions typically aim at improving growing conditions for the trees that are left behind (Smith et al. 1997, Nyland 2002). Other aspects of thinning, related to the ecosystem's ability to adapt, include the potential establishment of advanced regeneration (Kuehne and Puettmann 2008). Furthermore, thinning can also increase the amount and diversity of understory vegetation, especially the establishment of early successional species (Wilson and Puettmann 2007, Ares et al. 2010). In the aftermath of extensive overstory tree mortality, such as found after mountain pine beetle outbreaks (Griesbauer and Green 2006), advanced regeneration and vigorous understory vegetation may provide crucial ecosystem services, such as carbon sequestration, soil stabilization, and nutrient cycling. Another factor related to ecosystem adaptability is that the increased vigor of residual trees may eventually lead to higher seed production (Greene et al. 1999), which facilitates tree reestablishment after disturbances (Shatford et al. 2007). Understory vegetation, advanced regeneration, and increased tree vigor can thus be viewed as legacy elements that are crucial for the reassembly of an ecosystem after disturbances (Gunderson and Holling 2002). As can be gleaned from this brief discussion, density management regimes aimed to prepare forests for global change by increasing the ability of ecosystems to adapt to altered conditions may be quite different from prescriptions designed to improve timber productivity.

Variable-retention and variable-density thinning treatments provide a second example of changes in decision criteria when managing forests as complex adaptive systems. Variable-density treatments are a common suggestion for increasing spatial variability in homogenous stands, often with the goal of increasing the diversity of wildlife habitat (e.g., Carey 2000). Linking variable-density treatment more directly to aspects of adaptability and resilience will influence decisions about the spatial layout of silvicultural treatments. In addition to aspects such as wildlife habitat or light requirement for tree regeneration, silviculturists managing forests as complex adaptive systems would also consider whether any prescriptions increase or decrease the number of spatial scales at which various ecosystem functions and processes are acting (see discussion above, Peterson et al. 1998) and modify the spatial layout accordingly.

Shifting from monoculture to mixed-species stands has long been viewed as increasing the forest's ability to deal with disturbances (e.g., Gayer 1886, Kelty et al. 1992). Traditionally, the species choice is typically driven by compatibility ingrowth patterns, e.g., a shade-intolerant species that will overtop a shade-tolerant species (Pretzsch 2005). Managing forests as complex adaptive systems would add other factors to these decisions, again providing a closer link to aspects of adaptability and resilience. One such aspect is whether or not the "added" species increase the response-type diversity of key ecosystem functions. For example, species mixes that increase the diversity of regeneration modes (e.g., sprouting, serotinous cones, and seedbanking) are more likely to ensure the forest's ability to regenerate naturally after a wider range of perturbations, and species choices would reflect this.

The previous discussion of silvicultural treatments focused on tree establishment and growth. However, it is important to keep in mind that all plant and animal species may be affected by global change and by silvicultural treatments. The knowledge base detailing such impacts is often slimmer than our understanding of tree responses. Thus, several authors suggest that other aspects, such as protection of sensitive areas or silvicultural practices modified to accommodate the "lifeboating function," may become even more important (e.g., Franklin et al. 1997, Rosenvald and Lohmus 2008). It is important that legacy components will not only be selected for lifeboating and structural enhancement, however, but also with ecosystem adaptability in mind. This should include aspects discussed previously, such as increasing the variety of regeneration modes, as well as increasing the range of spatial and temporal scales of ecosystem processes.

Act Now or Time to Wait? What Can I Do Differently Tomorrow?

Silviculture has a long history of successfully adapting to changing conditions (Puettmann et al. 2009), but the challenges provided by global change are daunting. Obviously, silviculturists can not afford to wait until researchers have worked out the solutions, such as specific operational guidance for the purpose of increasing the adaptive capacity and resilience of forest ecosystems. However, proactive silviculturists have numerous options that can be tailored to their specific situations. Whichever option silviculturists choose, no single practice will work in isolation; applying practices in the context of adaptive forest management within a monitoring framework may be our best option at this time (Bolte et al. 2009).

The diversity of conditions likely requires a suite of different silvicultural treatments in response to global change (Campbell et al. 2009). Based on their objectives, it is useful to organize treatments into silvicultural practices that aim to increase resistance to change, practices that promote resilience to change, and practices that facilitate the ecosystem's ability to adapt to changing conditions (Millar et al. 2007, Stephens et al. 2010). Several silvicultural treatments, such as fuelbreaks, thinning operations, and weed and pest control practices can simultaneously increase resistance and resilience. Assisted migration and, more generally, managing forests as complex adaptive systems (e.g., by increasing the diversity of functional and response-type traits), would be examples of enabling forest ecosystems to adapt to change (Campbell et al. 2009).

At one end of the spectrum, there may be no need to do anything differently (Brang et al. 2008). For example, in even-aged stands with healthy, fast-growing trees close to rotation age, slow-acting changes such as temperature increases may not be enough to appreciably impact the forest ecosystem before harvest—at least in terms of tree growth and vigor. Even faster-acting disturbances, such as newly appearing diseases, can be accommodated simply by harvesting earlier than the planned rotation age and replanting with a species not affected by the disease. In other settings, silviculturists may focus on increasing the resistance of forests and be best served by applying multiple treatments from a suite of silvicultural practices, such as those listed in Table 1 (with adjustments to reflect no-analog conditions in the future as discussed previously). However, all these practices will increase the costs and short-term environmental impacts of forest management. Additionally, they may have only limited value if climate and other ecological and environmental conditions continue to change.

Increasing the ability of forests to adapt to changing conditions may be the best long-term solution. Managing forests as complex adaptive systems is still a theoretical concept, and research into practical applications is just beginning. The examples described previously highlight how a shift in focus can be initiated within the current set of management practices, however, by more formally assessing silvicultural treatments in relation to their impacts on adaptability and resilience, i.e., by shifting the emphasis of decisionmaking criteria for silvicultural prescriptions. Many of these criteria are not yet determined, and much work needs to be done before this approach can become a standard, reliable option for management. Some of these changes in decisionmaking criteria will likely lead to increased costs or short-term reductions in productivity. This may be the price we pay to increase management flexibility and create options that ensure ecosystem adaptability and long-term forest productivity in a changing and uncertain world. On the other hand, managing forests as complex adaptive systems may provide opportunities to reduce management inputs, and thus, costs (e.g., by accepting natural regeneration of different species in areas with high mortality of planted seedlings, if this leads to an increase in response type diversity). Finding such opportunities, as well as finding an appropriate balance between current ecosystem productivity and future adaptability, will require much work from researchers and practitioners. If history is any indication, silviculturists are up to the challenge.

Literature Cited

Aitken, S.N., S. Yeaman, J.A. Holliday, T. Wang, and S. Curtis-McLane. 2008. Adaptation, migration or extirpation: Climate change outcomes for tree populations. *Evol. Applic.* 1:95–111.

Allen, T.F.H., J.A. Tainter, and T.W. Hoekstra. 2003. *Supply-side sustainability*. Columbia University Press, New York. 440 p.

Anagnostakis, S.L. 1987. Chestnut blight: The classical problem of an introduced pathogen. *Mycologia* 79(1):23–37.

Anderson, P. 2008. *Silviculture and climate change.* US For. Serv., Climate Change Resource Center. Available online at www.fs.fed.us/ccrc/topics/silviculture.shtml; last accessed Jan. 11, 2010.

Ares, A., A. Neill, and K.J. Puettmann. 2010. Understory abundance, species diversity and functional attribute response to thinning in coniferous stands. *For. Ecol. Manag.* 260(7): 1104–1113.

Bergeron, Y., B. Harvey, A. Luduc, and S. Gauthier. 1999. Forest management guidelines based on natural disturbance dynamics: Stand and forest-level considerations. *For. Chron.* 75:49–54.

Binkley, D. 1983. Ecosystem production in Douglas-fir plantations: Interaction of red alder and site fertility. *For. Ecol. Manag.* 5:215–227.

Bolte, A., C. Ammer, L. Magnus, P. Madsen, G.J. Nabuurs, P. Schall, P. Spathelf, and J. Rock. 2009. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scand. J. For. Res.* 24(6):473–482.

Brand, F.S., and K. Jax. 2007. Focusing the meaning(s) of resilience: Resilience as a descriptive concept and a boundary object. *Ecol. Soc.* 12:16.

Brang, P., H. Bugmann, A. Bürgi, U. Mühlethaler, A. Rigling, and R. Schwitter. 2008. Klimawandel als waldbauliche Herausforderung (Climate change as a challenge for silviculture). *Schweiz. Z. Forst.* 159(10):362–373.

Brock, W.A., and S.R. Carpenter. 2010. Interacting regime shifts in ecosystems: implication for early warnings. *Ecol. Monogr.* 80(3):353–367.

Campbell, E.M., S.C. Saunders, K.D. Coates, D.V. Meidinger, A. MacKinnon, G.A. O'Neill, D.J. MacKillop, S.C. DeLong, and D.G. Morgan. 2009. *Ecological resilience and complexity: A theoretical framework for understanding and managing British Columbia's forest ecosystems in a changing climate.* Tech. Rep. 055. BC Min. For. Range, For. Sci. Prog., Victoria, BC, Canada. Available online at www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr055.htm; last accessed Jan. 10, 2011.

Carey, A.B. 2000. Effects of new forest management strategies on squirrel populations. *Ecol. Applic.* 10(1):248–257.

Carpenter, S.R., B. Walker, J.M. Anderies, and N. Abel. 2001. From metaphor to measurement: Resilience of what to what? *Ecosystems* 4:765–781

Carpenter, S.R., and W.A. Brock. 2006. Rising variance: A leading indicator of ecological transition. *Ecol. Lett.* 9(3):308–315.

Childs, S.W., and L.E. Flint. 1987. Effect of shadecards, shelterwoods, and clearcuts on temperature and moisture environments. *For. Ecol. Manag.* 18:205–217.

Cissel, J.H., F.J. Swanson, and P.J. Weisberg. 1999. Landscape management using historical fire regimes: Blue River, OR. *Ecol. Applic.* 9:1217–1231.

Climate Change Science Program (CCSP). 2009. *Thresholds of climate change in ecosystems.* Rep. by the US Climate Change Science Program (CCSP) and the Subcommittee on Global Change Research, Fagre, D.B., C.W. Charles, C.D. Allen, C. Birkeland, F.S. Chapin III, P.M. Groffman, G.R. Guntenspergen, A.K. Knapp, A.D. McGuire, P.J. Mulholland, D.P.C. Peters, D.D. Roby, and G. Sugihara (eds.). US Geological Survey, Reston, VA. 156 p.

Coates, K.D., and P.J. Burton. 1997. A gap-based approach for development of silvicultural systems to address ecosystem management objectives. *For. Ecol. Manag.* 99:337–354.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B.M. Wotton. 2001. Climate change and forest disturbances. *Bioscience* 51: 723–734.

Daly, C., D.R. Conklin, and M.H. Unsworth. 2009. Local atmospheric decoupling in complex topography alters climate change impacts. *Int. J. Climatol.* 2009:1–8.

Delic, K.A., and R. Dum. 2006. *On the emerging future of complexity sciences. Ubiquity*. Available online at www.acm.org/ubiquity/views/v7i10_complexity.html; last accessed Mar. 19, 2010.

Drever, C.R., G. Peterson, C.M. Messier, Y. Bergeron, and M. Flannigan. 2006. Can forest management based on natural disturbances maintain ecological resilience? *Can. J. For. Res.* 36:2285–2299.

Drew, T.J., and J.W. Flewelling. 1979. Stand density management: An alternative approach and its application to Douglas-fir plantations. *For. Sci.* 25:518–532.

Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, B. Walker, J. Bengtsson, F. Berkes, J. Colding, K. Danell, M. Falkenmark, L. Gordon, R. Kasperson, N. Kautsky, A. Kinzig, S. Levin, K.G. Mäler, F. Moberg, L. Ohlsson, P. Olsson, E. Ostrom, W. Reid, J. Rockström, H. Savenije, and U. Svedin. 2002. Resilience and sustainable development: Building adaptive capacity in a world of transformations. Scientific Background Paper on Resilience for the process of The World Summit on Sustainable Development on behalf of The Environmental Advisory Council to the Swedish Government. *Ambio* 31(5):437–440.

Forrester, D.I., J. Bauhus, and A.L. Cowie. 2005. On the success and failure of mixed-species tree plantations: Lessons learned from a model system of *Eucalyptus globules* and *Acacia mearnsii. For. Ecol. Manag.* 209(1–2):147–155.

Franklin, J.F., H.H. Shugart, and M.E. Harmon. 1987. Tree death as an ecological process. *BioScience* 27:550–556.

Franklin, J.F., D.R. Berg, D.A. Thornburgh, and J.C. Tappeiner. 1997. Alternative silvicultural approaches to timber harvesting: Variable retention harvesting systems. P. 111–139 in *Creating a forestry for the 21st century*, Kohm, K., and J.F. Franklin (eds.). Island Press, Washington, DC.

Gayer, K. 1886. *Der gemischte Wald, seine Begründung und Pflege, insbesondere durch Horst- und Gruppenwirtschaft.* (The mixed forest—Its establishment and treatments.) Parey Verlag, Berlin, Germany. 168 p.

Greene, D.F., J.C. Zasada, L. Sirois, D. Kneeshaw, H. Morin, I. Charron, and M.J. Si-

MARD. 1999. A review of the regeneration dynamics of North American boreal forest tree species. *Can. J. For. Res.* 29:824–839.

GRIESBAUER, H.P., AND D.S. GREEN. 2006. Examining the utility of advance regeneration for reforestation and timber production in unsalvaged stands killed by the mountain pine beetle: Controlling factors and management implications. *BC J. Ecol. Manag.* 7(2):81–92.

GRIESBAUER, H.P., AND D.S. GREEN. 2010. Assessing the climatic sensitivity of Douglas-fir at its northern range margins in British Columbia, Canada. *Trees Struct. Funct.* 24(2):375–289.

GUNDERSON, L.H., AND C.S. HOLLING. 2002. *Panarchy: Understanding transformations in human and natural systems.* Island Press, Washington, DC. 508 p.

HAACK, R.A. 2006. Exotic bark- and wood-boring Coleoptera in the United States: Recent establishments and interceptions. *Can. J. For. Res.* 36:269–288.

HEMERY, G. 2008. Forest management and silvicultural responses to projected climate change impacts on European broadleaved trees and forests. *Int. For. Rev.* 10(4):591–607.

HOBBS, R.J., D.N. COLE, L. YUNG, E.S. ZAVALETA, G.H. APLET, F.S. CHAPIN III, P.B. LANDRES, D.J. PARSONS, N.L. STEPHENSON, P.S. WHITE, D.M. GRABER, E.S. HIGGS, C.I. MILLAR, J.M. RANDALL, K.A. TONNESSEN, AND S. WOODLEY. 2010. Guiding concepts for park and wilderness stewardship in an era of global environmental change. *Front. Ecol. Environ.* 8:483–490.

HOLLING, C.S. 1996. Engineering resilience versus ecological resilience. P. 31–44 in *Engineering within ecological constraints*, P. C. Schulze (ed.). National Academy Press, Washington, DC.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). 2007. *Climate change 2007: The physical science basis.* Contribution of Working Group I to the Fourth Assessment Rep. of the Intergovernmental Panel on Climate Change, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, UK, and New York. 996 p.

IVES, A.R., AND S.R. CARPENTER. 2007. Stability and diversity of ecosystems. *Science* 317:58–62.

JAKOBSEN, M.K. 2001. *Textbook 2—Tools for preserving woodland biodiversity.* History and principles of close to nature forest management: A central European perspective. Nature Conservation Experience Exchange, Naconex. Available online at www.pro-natura.net/naconex/news5/E2_11.pdf; last accessed Mar. 17, 2010.

KELTY, M.J., B.C. LARSON, AND C.D. OLIVER. 1992. *The ecology and silviculture of mixed-species forests.* Kluwer Academic Publishers, Dordrecht, Netherlands. 287 p.

KIMMINS, J.P., AND D.P. LAVENDER. 1992. Ecosystem-level changes that may be expected in a changing global climate: A British Columbia perspective. *Environ. Toxicol. Chem.* 11:1061–1068.

KOHM, K.A., AND J.F. FRANKLIN (EDS). 1997. *Creating a forestry for the 21st century: The science of ecosystem management.* Island Press, Washington, DC. 475 p.

KUEHNE, C., AND K.J. PUETTMANN. 2008. Natural regeneration in thinned Douglas-fir stands in western Oregon. *J. Sustain. For.* 27:246–274.

KÜSSNER, R. 2003. Mortality patterns of *Quercus*, *Tilia*, and *Fraxinus* germinants in a floodplain forest on the river Elbe, Germany. *For. Ecol. Manag.* 173(3):37–48.

LANGVALL, O., AND G. ORLANDER. 2001. Effects of pine shelterwoods on microclimate and frost damage to Norway spruce seedlings. *Can. J. For. Res.* 31:155–164.

LAWLER, J.J., T.H. TEAR, C. PYKE, M.R. SHAW, P. GONZALEZ, P. KAREIVA, L. HANSEN, L. HANNAH, K. KLAUSMEYER, A. ALDOUS, C. BIENZ, AND S. PEARSALL. 2010. Resource management in a changing and uncertain climate. *Front. Ecol. Environ.* 8(1):35–43.

LEVIN, S.A. 1998. Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* 1:431–436.

LINDNER, M., J. GARCIA-GONZALO, M. KOLSTRÖM, T. GEEN, R. REGUERA, M. MAROSCHEK, R. SEIDL, M.J. LEXER, S. NETHERER, A. SCHOPF, A. KREMER, S. DELZON, A. BARBATI, M. MARCHETTI, AND P. CORONA. 2007. *Impacts of climate change on European forests and options for adaptation.* Rep. AGRI-2007-G4-06 to the European Commission Directorate-General for Agriculture and Rural Development, Brussels, Belgium. 173 p.

MALMSHEIMER, R.W., P. HEFFERNAN, S. BRINK, D. CRANDALL, F. DENEKE, C. GALIK, E. GEE, J.A. HELMS, N. MCCLURE, M. MORTIMER, S. RUDDELL, M. SMITH, AND J. STEWART. 2008. Forest management solutions for mitigating climate change in the United States. *J. For.* 106(4/5):125–162.

MCDOWELL, N.G., J.R. BROOKS, S.A. FITZGERALD, AND B.J. BOND. 2003. Carbon isotope discrimination and growth response of old (Pinus) ponderosa trees to stand density reductions. *Plant Cell Environ.* 26:631–644.

MCDOWELL, N.G., H.D. ADAMS, J.D. BAILEY, M. HESS, AND T.E. KOLB. 2006. Homeostatic maintenance of ponderosa pine gas exchange in response to stand density changes. *Ecol. Applic.* 16:1164–1182.

MCKENNEY, D.W., J.H. PEDLAR, K. LAWRENCE, K. CAMPBELL, AND M.F. HUTCHINSON. 2007. Potential impacts of climate change on the distribution of North American trees. *BioScience* 57:939–948.

MILLAR, C.I., N.L. STEPHENSON, AND S.L. STEPHENS. 2007. Climate change and forests of the future: Managing in the face of uncertainty. *Ecol. Applic.* 17:2145–2151.

MOTE, P.W., E.A. PARSON, A.F. HAMLET, W.S. KEETON, D. LETTENMAIER, N. MANTUA, E.L. MILES, D.W. PETERSON, D.L. PETERSON, R. SLAUGHTER, AND A.K. SNOVER. 2003. Preparing for climatic change: The water, salmon, and forests of the Pacific Northwest. *Climatic Change* 61:45–88.

NABUURS, G.J., A. PUSSINEN, T. KARJALAINEN, M. ERHARD, AND K. KRAMER. 2002. Stemwood volume increment changes in European forests due to climate change—A simulation study with the EFISCEN model. *Glob. Change Biol.* 8:304–316.

NORBERG, J., AND G.S. CUMMING (EDS.). 2008. *Complexity theory for a sustainable future.* Columbia University Press, New York. 352 p.

NYLAND, R.D. 2002. *Silviculture: Concepts and applications*, 2nd Ed. The McGraw-Hill Co., New York. 682 p.

OLIVER, C.D., AND B.C. LARSON. 1996. *Forest stand dynamics.* Wiley, New York. 544 p.

PAQUETTE, A., AND C. MESSIER. 2009. The role of plantations in managing the world's forests in the Anthropocene. *Front. Ecol. Environ.* 8:27–34.

PARROTT, L. 2010. Measuring ecological complexity. *Ecol. Indic.* 10:1069–1076.

PEREZ-GARCIA, J., L.A. JOYCE, A.D. MCGUIRE, AND X. XIAO. 2002. Impacts of climate change on the global forest sector. *Climatic Change* 54(4):439–461.

PETERSON, G., C.R. ALLEN, AND C.S. HOLLING. 1998. Ecological resilience, biodiversity, and scale. *Ecosystems* 1:6–18.

POLAND, T.M., AND D.G. MCCULLOUGH. 2006. Emerald ash borer: Invasion of the urban forest and threat to North America's ash resource. *J. For.* 104:118–124.

PRETZSCH, H. 2005. Diversity and productivity in forests: Evidence from long-term experimental plots. P. 41–64 in *Forest diversity and function: Temperate and boreal systems*, Scherer-Lorenzen, M., C. Korner, and E.-D. Schulze (eds.). Springer-Verlag, Heidelberg, Germany.

PRETZSCH, H., P. BIBERAND, AND J. DURSKY. 2002. The single tree-based stand simulator SILVA: Construction, application and evaluation. *For. Ecol. Manag.* 162:3–21.

PUETTMANN, K.J. 2009. Silviculture in times of global changes and uncertainty: What is on the horizon? *West. For.* 54(5):1–4.

PUETTMANN, K.J., K.D. COATES, AND C. MESSIER. 2009. *A critique of silviculture: Managing for complexity.* Island Press, Washington, DC. 206 p.

RAGAUSKAS, A.J., M. NAGY, D.H. KIM, C.A. ECKERT, J.P. HALLETT, AND C.L. LIOTTA. 2006. From wood to fuels: Integrating biofuels and pulp production. *Ind. Bio.* 2(1):55–65.

RESILIENCE ALLIANCE. 2011. *Bibliography*. Available online at www.resalliance.org/index.php/bibliography; last accessed Jan. 11, 2011.

ROSENVALD, R., AND A. LOHMUS. 2008. For what, when, and where is green-tree retention better than clear-cutting? A review of the biodiversity aspects. *For. Ecol. Manag.* 255(1):1–15.

SALA, A., G.D. PETERS, L.R. MCINTYRE, AND M.G. HARRINGTON. 2005. Physiological responses of ponderosa pine in western Montana to thinning, prescribed burning, and burning season. *Tree Physiol.* 25:339–348.

SCHMIDT, U.E. 2009. Wie erfolgreich was das Dauerwaldkoncept bislang: Eine historische analyse. (How successful was the Dauerwald movement: A historical analysis.) *Schweiz. Z. Forst.* 160:144–151.

Schütz, J.P. 2009. Die Prinzipien des naturnahen Waldbaus sind auch bei Klimawandel gültig (Essay). (The principles of ecoforestry are also valid in a changing climate [essay].) *Schweiz. Z. Forst.* 160(3):68–73.

Seastedt, T.R., R.J. Hobbs, and K.N. Suding. 2008. Management of novel ecosystems: Are novel approaches required? *Front. Ecol. Environ.* 6:547–553.

Seymour, R.S., A.S. White, and P.G. deMaynadier. 2002. Natural disturbance regimes in northeastern North America—Evaluating silvicultural systems using natural scales and frequencies. *For. Ecol. Manag.* 155:357–367.

Shanley, P., A.R. Pierce, S.A. Laird, and A. Guillén (eds.). 2002. *Tapping the green market: Certification and management of non-timber forest products.* Earthscan, London, UK. 456 p.

Shatford, J.P.A., D.E. Hibbs, and K.J. Puettmann. 2007. Conifer regeneration after forest fire in the Klamath-Siskiyous: How much, how soon? *J. For.* 105(3):139–146.

Smith, D.M., B.C. Larson, M.J. Kelty, and P.M.S. Ashton. 1997. *The practice of silviculture, applied forest ecology*, 9th Ed. John Wiley & Sons, New York. 560 p.

Smit, B., I. Burton, R.J.T. Klein, and R. Street. 1999. The science of adaptation: a framework for assessment. *Mitig. Adapt. Strat. Glob. Change* 4:199–213.

Solé, R.V., and J. Bascompte. 2006. *Self-organization in complex ecosystems.* Princeton University Press, NJ. 373 p.

Spiecker, H., K. Mielikäinen, M. Köhl, and J.P. Skovsgaard (eds.). 1997. *Growth trends in European forests.* Springer, Berlin. 372 p.

Spittlehouse, D.L., and R.B. Stewart. 2003. Adaptation to climate change in forest management. *BC J. Ecol. Manag.* 4(1):7–17.

St. Clair, J.B., and G.T. Howe. 2009. Genetic options for adapting forests to climate change. *West. For.* 54(1):9–11.

Stephens, S.L., C.I. Millar, and B.M. Collins. 2010. Operational approaches to managing forests of the future in Mediteranean regions within a context of changing climates. *Environ. Res. Lett.* 5:1–9.

Wagner, R.G., K.M. Little, B. Richardson, and K. Mc.Nabb. 2006. The role of vegetation management for enhancing productivity of the world's forests. *Forestry* 79:57–79.

Waldrop, M.M. 1992. *Complexity: The emerging science and the border of order and chaos.* Touchstone, New York. 384 p.

Wallin, K.F., T.E. Kolb, K.R. Skov, and M.R. Wagner. 2004. Seven-year results of the influence of thinning and burning restoration treatments on pre-settlement ponderosa pines at the Gus Pearson Natural Area. *Restor. Ecol.* 12: 239–247.

Walther, G.R. 2003. Plants in a warmer world. *Perspect. Plant Ecol. Evolut. System.* 6(3):169–185.

Wilson, D., and K.J. Puettmann. 2007. Density management and biodiversity in young Douglas-fir forests: Challenges of managing across scales. *For. Ecol. Manag.* 246:123–134.

Yachi, S., and M. Loreau. 1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. *Proc. Natl. Acad. Sci. USA* 96(4):1463–1468.

Zimmermann, N.E., N.G. Yoccoz, T.C. Edwards Jr., E.S. Meier, W. Thuiller, A. Guisan, D.R. Schmatz, and P.B. Pearman. 2009. Colloquium papers: Climatic extremes improve predictions of spatial patterns of tree species. *Proc. Natl. Acad. Sci. USA* 106(suppl. 2):19723–19728.