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POLICY PERSPECTIVES

From Management to Stewardship: Viewing Forests As Complex Adaptive Systems in an Uncertain World

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Abstract

The world's forests and forestry sector are facing unprecedented biological, political, social, and climatic challenges. The development of appropriate, novel forest management and restoration approaches that adequately consider uncertainty and adaptability are hampered by a continuing focus on production of a few goods or objectives, strong control of forest structure and composition, and most importantly the absence of a global scientific framework and long-term vision. Ecosystem-based approaches represent a step in the right direction, but are limited in their ability to deal with the rapid pace of social, climatic, and environmental changes. We argue here that viewing forest ecosystems as complex adaptive system provides a better alternative for both production- and conservation-oriented forests and forestry. We propose a set of broad principles and changes to increase the adaptive capacity of forests in the face of future uncertainties. These span from expanding the sustained-yield, single-good paradigm to developing policy incentives and interventions that promote self-organization and integrated social-ecological adaptation.

Introduction

Today's forests cover about 30% of the global land area and provide essential ecosystem goods and services. Globally, forests face unprecedented biological, political, social and, climatic challenges (Table 1). Although forest management and restoration approaches have had a long history of responding to changing ecological and social conditions (Figure 1), they are increasingly failing to adapt to these unprecedented challenges (Puettmann *et al*. 2009; Messier *et al*. 2013). Recognizing that destructive harvesting practices would not sustain wood production, forestry developed as a scientific and management field in the 18th century in central Europe. Inspired by trends in philosophy, economics, and agriculture, newly developed rules and principles of forestry focused on improving timber or game production efficiency, mostly through homogenization and regulation. This

Table 1 Current and novel unprecedented biological, political, social, climatic global scale challenges facing forest management worldwide

Challenges	Examples
Current challenges stemming from past land uses and forestry practices	
Integration of divergent needs and interests of forest stakeholders in management planning. Greater public scrutiny of forest management practices.	• Legal challenges to U.S. Forest Service management plans and practices • Open debate between conservation interests demanding strict forest protection and local forest users demanding access to forest resources worldwide
Environmental concerns resulting from conversion of land use to monospecific plantations and short rotation crops.	• Expansion of oil palm plantations on previously forested land in the tropics will reduce habitat for native species • Loss of species and genetic diversity in many regions, especially in Scandinavia, will lead to reduced resilience and adaptive capacity
Novel challenges emerging from globalization of trade and markets and rapidly changing climate and ownership patterns	
Developments in foreign countries influence local management due to globalization of markets and trade.	• Energy policies of the European Union influence forestry practices in the southeastern United States and other places by providing a new, attractive market for pellets • The Chinese economy impacts forest harvesting trends in the western United States, Canada, and Europe
Alteration of composition, function, and ecosystem services by invasive species.	• Spread of invasive emerald ash borer, woolly adelgid, gypsy moth, and many other exotic insects in North America from Asia and Europe due to increasing trading has led to changes in forest composition and carbon cycles • North American beaver in Southern Patagonia has resulted in deforestation and hydrological changes • Cogongrass inhibits pine regeneration in the Southeastern United States
Large-scale mortality due to unprecedented severe natural disturbances, including windstorms, fires, and native insect outbreaks due to climate change.	• Large windthrows in central Europe in the 1990s • Recent extensive bark beetle outbreaks in Western North America • Increased frequency of high severity forest fires in southwestern North America, southern Europe, Indonesia, and Amazonia • Expected increased wildfire risk in the Mediterranean area.
Climate change impacts on various components (flora, fauna, pests) of forest ecosystems.	• Shift in the phenology of plants, herbivorous insects, and insectivorous bird • Decoupling host–prey and host–herbivore interactions
High investment costs and long term, uncertain incomes because of unpredictable markets result in land abandonment by forest owners.	• Abandonment of timber plantations in Japan • Frequent turnover of ownership in United States • Lack of management interest and large scale changes in forest practices by small woodland owners in Europe
Increasing concentration of forest ownership and insecure land tenure	• Concentration to large ownerships by Real Estate Investment Trusts as timber companies divest themselves of their forestlands in the United States • Land grabs and land scarcity in developing countries

narrow single-good or objective, command-and-control approach has strongly influenced forest management practices on a global scale. They form the basis of a highly productive and efficient wood industry that is still prevalent in many parts of the world, especially, but not only, on the 30% of global forests which have "commodity production" as their primary designation (FAO 2010).

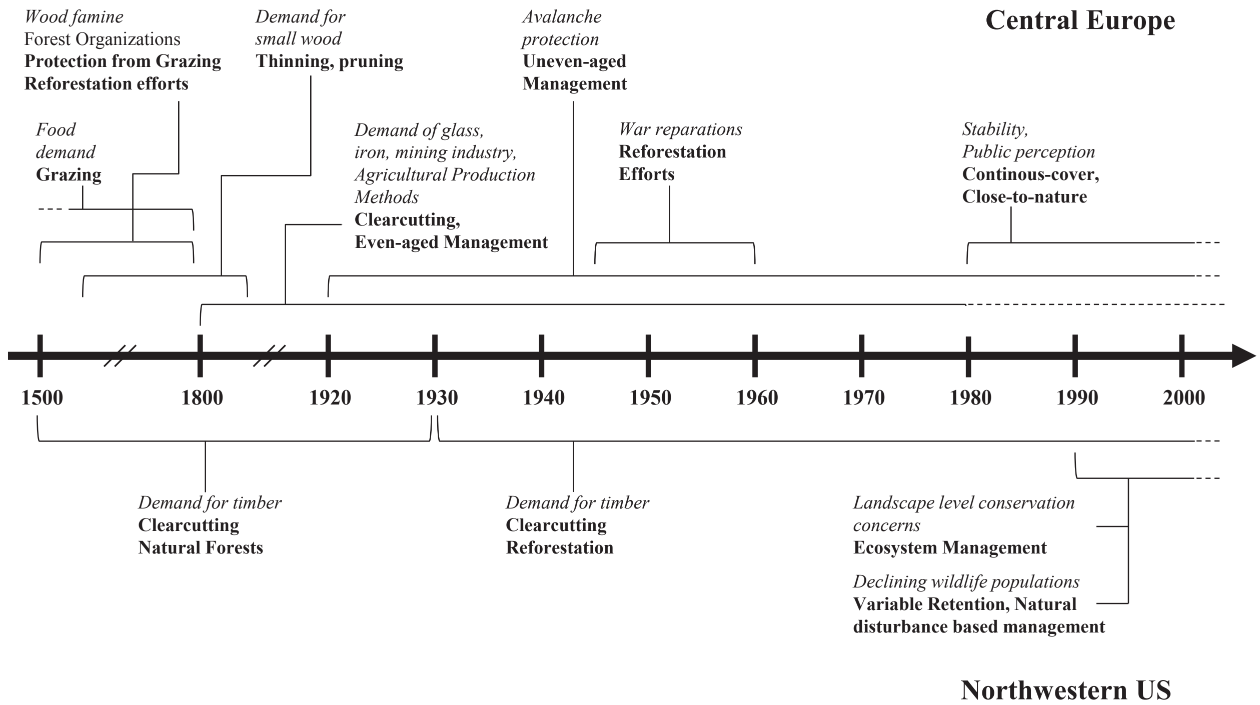

Figure 1 Diagram highlighting the major factors (in italics) influencing forestry and the associated development of management approaches and practices (in bold) in Central Europe (above) and North America (below). The figure is not a complete historical description; only major trends are listed. For a more detailed description of the historical development of forestry as related to social and economic factors, see Puettmann *et al.* (2009). Note that the *x*-axis is not to scale.

This top–down, centralized, one-size-fits-all approach reduces the range of variation and self-organization (i.e., process by which some form of global order or emergent properties arise out of local strong interactions) needed for the environmental, social, or economic system to adapt rapidly and efficiently to novel conditions (Holling & Meffe 1996; Messier *et al.* 2013). New forest management and conservation approaches have emerged in several places around the world to address local concerns and controversies (Figure 2). For example, early work on ecosystem management arose from a need to assess large-scale, landscape-level conservation goals. Uneven-aged management (Matthews 1989) and the more recent close-to-nature (Jacobson 2001) and continuous-cover forestry approaches (Pommering & Murphy 2004) put a heavy emphasis on optimizing the growth and value of individual trees (vs. stands) and maintaining the continuity of forest cover and ecosystem processes (Schütz 2001). Variable retention forestry in Canada, United States, northern Europe, Argentina, Chile, and Australia emphasizes the value of carrying diverse structural legacies such as live and dead standing trees and small patches of intact forest into postharvest, future stands and/or maintaining certain habitat characteristics to support selected species (Gustafsson *et al.* 2012). Natural-disturbance-based forest management in many northern countries (Harvey *et al.* 2002) and reduced-impact logging in the tropics (Putz *et al.* 2008) have similar goals; they design management practices that mimic their respective local natural disturbance patterns. Multispecies forest plantations (Paquette & Messier 2010) and restoration of degraded forests (Rodrigues *et al.* 2009) have also been used to bolster existing forest fragments as reservoirs for biodiversity and provide urgently needed ecosystem services.

These ecosystem-based approaches represent a step in the right direction, as they acknowledge the importance of biodiversity and the interactions of neighborhood-, stand-, and landscape-level processes. Reflecting local concerns and controversies about traditional management approaches, they also focus on a broader set of management goals (Messier *et al.* 2013; Figure 2; Table 2). Like traditional preindustrial and timber-production management approaches, however, these new approaches are not designed to handle the emerging challenges stemming from the increased uncertainty and rapid pace of social, climatic, and environmental changes (see Table 14.1 in Messier *et al.* 2013; Mori *et al.* 2013). First, they were initiated as a response to local problems

Figure 2 Examples of emerging ecosystem-based silvicultural approaches used in different parts of the world. (a) Close-to-nature forestry in Germany, which focuses on reduced human intervention through single tree management; (b) Thinning even-aged Douglas-fir stands in Oregon, United States, to increase small-scale spatial variability; (c) Variable retention forestry in the boreal forest of Canada to ensure life boating of sensitive species; (d) Partial cutting in a mixed-wood boreal forest of Canada designed to reflect natural-disturbance-based forest management; (e) Natural regeneration of native species in the understory of a *Eucalyptus* plantation in Brazil as a way of restoring Atlantic Forest; and (f) Multispecies forest plantation of poplar and spruce in Canada to encourage both structural and compositional diversity (for a more detailed assessment of emerging management trends, see Messier *et al*. 2013).

Table 2 Comparison of traditional timber-based forest management, emerging new practices and the advocated new paradigm based on complexity theory. Changes from first to second column are mainly "patches" to traditional management, while changes from second to third column necessitate a paradigm shift where forests are seen as complex systems dynamically changing in response to global change

Traditional timber-based management	Emerging ecosystem-based management	Proposed new management approach based on complex adaptive system
Strong focus on timber	Strong focus on timber with an added concern for biodiversity	Focus on multiple ecosystem services and biodiversity
Sustained yield of a few tree species	Sustained yield of a few tree species and biodiversity	A new paradigm that integrates risk/flexibility/adaptability into scenarios of optimum yield level of various goods and services
Goal is to produce high yields of quality timber by simplifying forest structure and composition	Goal is to produce quality timber and maintain biodiversity by recreating some level of natural or previous conditions	Goal is to maintain the ability of the forest to produce quality timber and maintain biodiversity by favoring the capacity of the forests to adapt to the uncertain future conditions
Predictions about the future based on past conditions	Predictions about the future based on past conditions	Recognition of uncertainty in social, economic, and ecological future conditions and of the need to manage for adaptability
Management mainly at the stand scale	Management at both the stand and landscape scales	Management at multiple spatial and temporal scales that favor strong connection within patches and a mixture of among-patches connectivity and modularity
Management is based on viewing forests as inherently stable	Management recognizes the dynamic nature of forests	Management is based on the known dynamic and nonlinear nature of forests
Interventions to preclude self-organization and adaptation	Some self-organization and adaptation are tolerated	Interventions to promote self-organization and adaptation
Future harvesting projections based on models of timber yield and regeneration	Future harvesting projections based on ecosystem properties and forest regeneration	Future harvesting projections assess uncertainty and conditions leading to alternate steady states

and, as such, are "patches" to traditional management, i.e., they do not fully recognize the inherent uncertainty of the future and the need to promote adaptability instead of predictability. Consequently, they lack an underlying global scientific framework (Puettmann 2011), which makes it hard to coherently update them as new challenges and goals develop. Furthermore, these approaches are still rooted in the past forestry paradigm that sees forests and the goods and services forests provide as inherently stable and consequently focusses on the notion of an "optimal" forest structure and composition. This paradigm cannot be reconciled with the variability and uncertainty of both forest dynamics and the need for ecosystem goods and services such as wood and timber world markets under global change. For example, management practices designed to achieve specific stand structures or species compositions with a focus on specific wildlife habitats or historical disturbance regimes cannot necessarily be expected to improve the ecosystem's ability to adapt to a novel set of environmental conditions (Seastedt *et al*. 2008) or be able to respond to new wood markets and other novel social demands (Messier *et al*. 2013).

However, the "perfect storm" of unprecedented challenges facing both production- and conservation-oriented forestry (Table 1) now requires a new approach for the stewardship of the world forests. We propose that the limitations of traditional timber-based and emergent ecosystem-based forest management practices listed above indicate the need for and provide a unique opportunity to adopt a new, more scientifically coherent approach based on complexity theory (Table 2). Managing forests as complex adaptive systems (CAS) can provide a scientific foundation that not only acknowledges and accommodates uncertainty, but also helps production- and conservation-oriented forest managers and policy makers understand how ecosystems respond to change and how management can influence these responses. This understanding, achieved by viewing forests as CAS, is crucial to managing the novel ecosystems and responding appropriately to the new needs for good and services arising from global changes.

The CAS approach

The CAS approach views forests as complex systems composed of heterogeneous assemblages of individual agents (e.g., trees, animals, humans) closely interacting through flows involving markets, goods and various other ecosystem services (Figure and Box 1 of Filotas *et al.* 2014). Such systems have been characterized by their level of regularity (a CAS being between totally ordered and totally disordered, *sensu* Parrott 2010), capacity to self-organize following disturbance, and nonlinear behaviors (Levin 2005). CAS thinking has inspired ways for improving ecosystem resilience (defined here as the ability of ecosystems to recover from disturbances) and adaptability (capacity of a system to modify itself following disturbances so they maintain their basic functions; Chapin *et al*. 2006; Parrott & Meyer 2012), but applications to forest stewardship are rare, despite the fact that recent discussions emphasize the need to view natural-resource management issues in the context of social–ecological systems (for review, see Levin *et al.* 2013). For example, Parrot & Meyer (2012) showed how the implementation by marine managers of five key actions arising from complexity science has helped increase the resilience and adaptability of a new national marine park in the St Lawrence estuary in Quebec, Canada.

The main goal of this new approach should be to maintain or increase the adaptive capacity of forest ecosystems, including interactions between the natural and the human components, facing rapidly changing conditions. Adaptive capacity refers to the ability of the system to modify its structure and composition under changing social and ecological conditions without losing its essential functions (Gunderson 2000). In a forest restoration and management context, this may be the ability of forests to respond to changing host–pest interactions and climatic conditions, while at the same time continue to provide essential ecosystem services to society, such as wood in a global changing market, and to support habitats for native biodiversity (Puettmann 2014). The idea of the adaptive capacity of forest ecosystems does not receive adequate attention when the emphasis of environmental policies and "command and control" management is on optimal stand structures and composition or the production of a single good or service (e.g., wood, recreation, or water). In contrast, focusing on maintaining the adaptive capacity of forest ecosystems in the context of rapid and uncertain global socioenvironmental changes provides the best assurance that forests will continue to provide a full set of goods and services in a variable and uncertain future, including timber production, carbon storage, water quality, biodiversity, disease regulation, and maintenance of climate and soil properties.

What are the basic tenets of this new approach and how can it help managers and policy makers improve the overall resilience and adaptability of forest ecosystems facing an uncertain future? A set of general principles based on the various properties of CAS applies across the world's biomes and systems, although the application of these principles may differ significantly among regions, landowners, and even stands depending on local ecological, social, and economic conditions. These principles have in common the added emphasis on maintaining or increasing the adaptive capacity of ecological and social systems in the face of future uncertainties (Chapin III *et al*. 2010).

(1) *Replace the sustained single good or objective-yield paradigm with one that integrates risk/flexibility/adaptability into scenarios of sustained provision of various goods and services*. In most wood-production-oriented forest management plans, wood supply is the only good quantified and simulated and the objective is to maintain a constant flow over a long period of time without acknowledging the high degree of future uncertainty. Similarly, in most conservation-oriented forest management plans, the objective is to maintain or restore the forest to a certain ideal condition, again without acknowledging future uncertainty. This principle thus precedes all of the others and is necessary to allow this new paradigm to move forward. Certain forest jurisdictions in the world have begun to implement this principle. For example, in Flanders (Belgium), the current integrated forest management strategy does not indicate an optimal level of wood production to be maintained over the long term, but instead focuses more on flexibility, diversity, and opportunity in terms of various goods and services provided by the forest (B. Muys, personal communication). In the Mediterranean, managing for timber production alone is often uneconomical so forest managers and policy makers are slowly moving toward a more flexible approach that includes considerations for the provision of various nontimber goods and services, leading to much more flexibility in the forest management scenarios being considered (Messier *et al*. 2013). Although not fully based on the CAS approach, these jurisdictions have made a crucial first step in providing a more flexible long-term view of sustainability. As far as we know, the CAS approach is not being comprehensively applied

anywhere yet, in part because it also requires flexibility and adaptability in terms of human demands and expectations. Human communities that interact closely with forests, often depending on them for their livelihoods, must be able to adapt to variability in timber supply and other goods and services obtained from the forest.

(2) *Consider the taxonomic and functional diversity (i.e., range of ecological functions that organisms support in communities and ecosystems) of the tree species pool in terms of its ability to maintain a balance between diversity and redundancy and provide desired ecosystem goods and services in an ever-changing biological and social environment*. Focusing on building adaptive capacity shifts the decision matrix and emphasizes the diversity of functions that enable the community to better adapt to rapidly changing conditions. Fostering such a diversity of functions enables forestry operations to adapt to changes in market conditions, such as new manufacturing technologies, building or product standards, and consumer preferences. Functionally diverse, mixed-species stands support species with different biotic and abiotic sensitivities and recovery mechanisms following disturbances, thus ensuring the ability of ecosystems to self-organize, increasing their adaptive capacity. Novel approaches in financial theory and management science can facilitate the integration of such responses into forest growth and yield models (Knoke & Wurm 2006; Knoke *et al*. 2008) and thus facilitate the development of environmental policies and management practices that emphasize adaptive capacity when choosing species mixtures. Higher tree species diversity has also been shown to produce higher levels of ecosystem services (Gamfeldt *et al*. 2013). At the same time, there is growing evidence that diversity of species, management approaches, and products can promote the long-term sustainability of socioecological systems by increasing their resilience and adaptability (Chapin III *et al*. 2009).

(3) *Promote an optimal balance among modularity (i.e., the extent to which a system can be divided into independent units) and connectivity at multiple scales*. Ecosystems respond to changes at the full range of organizational levels, from somatic, epigenetic and genetic, to population, community, and landscape levels. Moreover, responses at each level interact with those at other levels, illustrative of the cross-scale hierarchical interactions typical of complex systems. Viewing management effects at different organizational levels and recognizing interactions among them will provide insight into potential positive or negative effects on self-organization pathways. Such an approach has been instrumental in bringing about changes to management strategies in the Bois-Francs region in southern Quebec (Canada) (Craven *et al*., in preparation). For this region, a group of researchers used a CAS approach to evaluate (1) possible future socioenvironmental threats, (2) the main current and future ecosystem services, (3) the spatial distribution and functional diversity of all tree species and their possible responses to anticipated threats, and (4) the connectivity and modularity (i.e., organized subunits that interact to influence system behavior) of the forest landscape. The forest management plan produced under this new paradigm focuses on key interventions to preserve functionally diverse and connected forest patches, thus increasing adaptive capacity, reducing the likelihood that the ecosystem will shift to an undesirable state in the future due to unprecedented socioenvironmental conditions.

(4) *Plan and assess interventions across a range of spatial and temporal scales, e.g., from plant neighborhoods to landscapes*. Adopting multiscale assessment procedures reduces the emphasis on an "optimal" stand structures and thus allows for a wider variety of acceptable stand structures, which in turn allows plant neighborhoods, stands, or groups of stands to act as independent interacting objects facilitating a CAS approach. A holistic multiscale assessment enables a deeper understanding of how a variety of organizations—human and biological—operating at different spatial and temporal scales may contribute to more effective managements. For example, a comparative study on the mixed outcomes of forest governance among local governments in Latin America found that localities that were well-connected to governance organizations at multiple spatial scales (provincial, regional, national) performed significantly better than systems without such cross-scale linkages (Andersson & Ostrom 2008).

(5) *Plan and develop long-term scenarios using new analytical tools and models that specifically acknowledge the prevalence of highly uncertain social, economic, climatic, and ecological conditions*. Incorporating uncertainty into management will require new models and tools, such as scenario analysis (Peterson *et al*. 2003), real options (Dixit & Pindyck 1994), and sensitivity analyses (i.e., planning, economic, and assessment approaches that incorporate uncertainty of future conditions, respectively). We know that social, economic, climatic, and ecological conditions 100 years from now will be unlike current or past conditions. Changing conditions must be anticipated rather than simply acknowledged as they occur because a reactive approach may be ineffective or detrimental

when dealing with long-lived organisms such as trees. This is probably the most pressing issue facing forest managers and policy makers today. Some cases will likely require conscious interventions to create a future forest structure and composition that increases resilience and adaptability to novel conditions such as a changing climate and invading exotic pests (Levin 2003; Hobbs *et al*. 2006).

(6) *Increase involvement of local communities and other stakeholders to ensure that future forests are better aligned with the needs and preferences of local people*. Recent developments in land trusts and community forests highlight the benefits of local involvement in forest management decisions. Advantages of such involvement include a broader base of policy support and enhanced forest benefits to local communities. Such efforts are becoming more common and are now acknowledged under the label "community forestry." Successful examples (e.g., the Kalso & District Community Forests in British Columbia, Canada) have even used community involvement to understand and integrate uncertainty into management plans through scenario analysis (see above). When local forest users actively participate in forest governance, the likelihood of achieving both biodiversity conservation and improved livelihoods is increased significantly (Persha *et al*. 2011). Furthermore, the involvement of local people who interact directly with forest resources increases the number of feedback linkages between human and natural systems and the speed of such feedbacks, which are essential components of adaptive management (Holling 1978) and sustainable resource use (Ostrom 2009).

(7) *Allow social–environmental systems to self-organize and adapt to novel biological, environmental, and social conditions*. Chapin *et al*. (2006) suggest four elements to achieve self-organization and adaptation in social–environmental systems: (1) foster human adaptability through learning and innovation, (2) enhance resilience by strengthening negative feedbacks that buffer the system against change, (3) reduce vulnerability by reducing negative anthropogenic impacts, and (4) facilitate transformation when current conditions can no longer be maintained. These replace the timber-based management paradigm in forestry (Holling & Meffe 1996) with an approach where interventions are minimized and aimed at facilitating bottom–up developments, inherent to complex systems, to maintain adaptive capacity while providing desired goods and services.

We recognize that many powerful forest management interests do not acknowledge an urgent need to change operating premises as they have profited well from current and past practices. Given the array of new challenges faced by forest managers (Table 1), these profits will likely not be sustained in the future without recognition of the features that enable forest ecosystems and the forestry sector to persist and adapt to rapidly changing conditions. Complex systems thinking views forests and their social–environmental systems as dynamic, nonlinear, self-organizing, open systems that are constantly changing and adapting. This approach appears to be our best option to ensure future sustainable provision of ecosystem goods and services through the creation of diverse, heterogeneous, resilient, and adaptable forest ecosystems.

Implementing these changes will not be easy; they require policy changes and interventions in the economic, political, and social arena. In this article, we discussed the following: (1) modifying current regulations and laws to redefine the concept of the sustainability of forest goods and services in light of uncertain and rapidly changing future conditions; (2) broadening the stakeholder base in decision making so that a more varied portfolio of good and services is considered and modelled; (3) monitoring a broader set of ecosystem services and promoting markets for these as financial incentives; (4) modernizing economic approaches to better reflect risks and diversifying forest products to reduce reliance on single species; and (5) integrating risk and uncertainty into management prescriptions, e.g., through scenario analysis exercises. Such policy changes would result in altered silvicultural treatments and management approaches. For example, recommendations number 4 and 5 would result in focusing reforestation efforts for restoration or production on tree species that are functionally complementary and redundant to those already present in the region to increase the resilience and adaptability of the forest to future uncertain conditions. These recommendations also highlight that a CAS view of forests, including the forestry sector, can be applied to forest management in a variety of settings. Changes in environmental policies and associated economic assessments that acknowledge future variability and uncertainty can result in economic and other incentives to landowners or forest managers seeking to apply approaches like those described here. We view it as critical that policy makers and production- and conservation-oriented forest managers work toward developing these initiatives.

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