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Simple Guidelines to Prepare Forests for Global Change: The Dog and the Frisbee

Abstract

Most suggestions for adapting forest management in times of rapid global change have focused on tree regeneration, mortality, and productivity under predicted future climates. Adaptation to other aspects of global change, such as invasive species or changes in social settings, has received much less attention, which may be partially due to the high unpredictability of such events. Based on a review of recent silvicultural practices and ecological theory with a special emphasis on complex adaptive systems, we propose three guidelines for increasing the likelihood that forests will provide desired levels of a variety of ecosystem services in an increasingly variable and uncertain future. Basically, the guidelines promote a system level instead of the traditional command and control approach (sensu Holling and Meffe 1996) to silviculture. They are based on the well-supported ecological notions that having a high diversity and redundancy of key elements that are well connected across spatial, temporal, and organizational scales will allow forests to adapt on their own in response to predictable and unpredictable perturbations without the need for major management interventions. The guidelines encourage the maintenance of stand structural and compositional diversity at multiple spatial and temporal scales, thus reinforcing cross-hierarchical interactions in ecosystems, with an emphasis on encouraging self-organization. We provide examples of silvicultural practices as they relate to these guidelines.

Keywords: resistance, resilience, adaptation, uncertainty, silviculture prescription

Introduction

Incorporating aspects of global change into management decisions is a major challenge for forest management (Puettmann 2011, Keenan 2015, Messier et al. 2019, Hagerman and Pelai 2019). Researchers have spent most of their efforts investigating vulnerability to one aspect of global change, namely climate change (Keenan 2015, Nagel et al. 2017). Hagerman and Pelai (2019) found over 200 journal articles that provide management recommendations regarding climate change. The recommendations focused mainly on silvicultural practices. The authors also point out that the vast majority (69%) of recommendations are "general, non-specific principles," such as "efficient adaptation of the forest management system," and that only about one-third of the articles suggested "actionable" recommendations (Hagerman and Pelai 2019). In this context, it is important to note that several aspects of climate change, such as increased temperatures and, to a lesser degree, changes in amount, timing, and patterns of precipitation may be predictable. This suggests a focus on specific adaptation processes on direct responses (sensu Meyers and Bull 2002) to local conditions, which is reflected in researchers being more specific in their recommendations. For example, in regions with predicted warmer and drier climate conditions, such as the Pacific Northwest of the USA, more intensive thinning was recommended to counter increased water stress and reduce fire risks (e.g., Chmura et al. 2011); for similar recommendations in other regions, see Kerhoulas et al. (2013) and Vilà-Cabrera et al. (2018).

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In contrast, other aspects of global change are much less predictable (Dukes et al. 2009) and in many cases more immediate (Keenan 2015, Lovett et al. 2016); e.g., the spread of native diseases to previously immune tree species, such as *Phytophthora ramorum* on Douglas-fir (*Pseudotsuga menziesii*) (Davidson et al. 2002). Similarly, the presence of invasive exotic insects or diseases is likely to increase with increased global trade (Hulme 2009, Countryman et al. 2018) and travel (Warziniack et al. 2013), resulting in an urgent need for novel management recommendations. For example, the presence of emerald ash borers (*Agrilus planipennis*) in the Midwest of the USA in 2002 changed management strategies regarding ash forests within a few years (Herms and McCullough 2014). The insect is now of concern in the Pacific Northwest (PNW), although it has not yet been detected there. Apprehensions about exotic diseases are further heightened by the planting of tree species outside of their native distribution in other regions of the globe. For example, Douglas-fir has been planted extensively in New Zealand, Europe, and Chile. This widespread distribution can facilitate the spread of Douglas-fir diseases from these regions into its native distribution in western North America, as has happened recently with an aggressive strain of *Phytophthora ramorum* (LeBoldus et al. 2017). The unpredictability of such events can result in managers applying random responses (sensu Meyers and Bull 2002) to the current environment. For example, foresters may hedge their bets by increasing tree species diversity without considering current and expected growing conditions and species traits. Consequently, fewer studies provide specific recommendations on how to deal with pest and/or disease outbreaks (Vilà-Cabrera et al. 2018), and other unpredictable threats.

Similarly, changes in political settings and market conditions cannot always be predicted, at least on a timescale relevant for forestry operations. For example, ballot measures can have an immediate impact on management practices, such as a recent ban on aerial pesticide applications being implemented or discussed in several counties in Oregon. Global trade agreements, regulations, and tariffs can all result in changes in management opportunities and limitations. Such impacts also require a different set of adaptation strategies. In addition, the long-term implications of adaptation strategies may be harder to predict (Vilà-Cabrera et al. 2018). Consequently, it should come as no surprise that most publications only provide general policy and marketing recommendations (Hagerman and Pelai 2019).

The objective of this paper is to help foresters to overcome these challenges and prepare forests for global change by providing three guidelines that are based on recent advances in ecology. Specifically, the guidelines are derived from the assessment that forests are prime examples of complex adaptive systems (Levin 1998, Rammel et al. 2007, Puettmann et al. 2009; Table 1). First, we highlight our recent conceptual work (Puettmann et al. 2009, Messier et al. 2013, Filotas et al. 2014, Messier et al. 2019). Then, because the practical implications of viewing forests as complex adaptive systems are not straightforward (Malik 1984, Levin 1999, Ramo 2009), we developed general guidelines that can direct foresters in their choices of specific management practices (see The dog and the Frisbee® analogy in Table 1, Concept 1). We then introduce three guidelines (with rationales) to encourage ecosystem adaptations to global change. Finally, we provide examples of conditions and practices as they relate to the guidelines as a way to show how these guidelines can be implemented in operational forestry settings.

By ordering our presentation as ecological theory, guidelines, and applications, we demonstrate that the guidelines can be flexible and apply to a myriad of situations. This is done to empower and encourage foresters to adapt the guidelines to their specific, local management settings. First, we provide the theoretical context (Puettmann et al. 2009, Messier et al. 2013) of the guidelines. Such an understanding can increase the confidence foresters need to be able to integrate the guidelines into their specific management settings and thus encourage ecosystem adaptive capacity. As visualized in Figure 1, an ecosystem with a higher adaptive capacity has a higher likelihood that it will take a developmental pathway that ensures the continued provision of desired ecosystem services (Puettmann 2014) while accommodating specific ownership opportunities and constraints (Table 2). At the same time, we present examples of management settings and silvicultural practices for foresters as they relate to the implementation of the three guidelines. We specifically focus on silvicultural practices in the western, Douglas-fir dominated portion of the PNW, but our aim is to encourage discussions that increase the ability of foresters to modify management approaches in a variety of ecological, economic, and social settings.

Ecological Theory—Adaptive Capacity of Forest Ecosystems

Based on our perspective of viewing forests as complex adaptive systems (CAS) (Puettmann et al. 2009, Messier et al. 2013), developing guidelines can be viewed as translating the properties of CAS, such as cross-scale hierarchical interactions (Table 1, Concept 2) into simple, easy to implement actions. This translation has been a challenge in several other fields, such as transportation and economics (Waldrop 1992). An assessment of how politicians and economists can deal with complex adaptive behavior of the stock market resulted in the dog-and-frisbee analogy (Table 1, Concept 1). Our guidelines are an application of this analogy, where simple rules can be successful at solving complex problems. Providing information about the theoretical basis—the CAS theory, can ensure that such an approach will not be viewed as a recipe or formula to be strictly followed. Instead, it should be viewed more like a coarse filter aimed at increasing the adaptive capacity of forests.

Forests are prime examples and exhibit all characteristics of CAS (Table 1, Concept 3) (Levin 1999, Messier et al. 2013, Filotas et al. 2014). Much can be gained from viewing forests as complex adaptive systems and specifically understanding how CAS respond to changing external conditions can be helpful when considering forest management options. Relevant changing external conditions in the context of forest management include a variety of global and social change issues (Dale et al. 2001, Kirilenko and Sedjo 2007, Bentz et al. 2010, Puettmann 2011). To understand how ecosystems respond to changing external conditions, forests are viewed in terms of CAS consisting of diverse components interacting with each other in linear and non-linear ways through multiple hierarchical scales and feedback loops (Levin 1998, Messier et al. 2013; Figure 2). Traditionally, forests have mostly been managed with a command and control approach (Holling and Meffe 1996) (Table 1, Concept 4). In contrast, viewing forests as CAS implies acknowledging that forests are self-organizing ecosystems and are organized through internal control instead of a central controller. Adaptations in terms of structure and composition to changing external conditions in CAS are driven by local, internal processes (Levin 1998, Camazine et al. 2001, Solé and Bascompte 2006) (Table 1, Concept 5). Thus, ecosystems react to perturbation through changes in 1) ecosystem components, 2) interactions among components within and across hierarchical scales, and 3) self-organizing processes that adapt over time. We developed three guidelines to address these three aspects. Examples of key ecosystem components that can be manipulated include altering the number and identity of tree species, the presence of other vegetation, and the insect, fungal, and wildlife communities. Examples of how plant-plant interactions within hierarchical levels can be altered include changing plant densities or spatial arrangements through thinning or weed control, or altering resource levels by fertilization. Examples of how interactions across hierarchical levels can be altered include changing levels of herbivore populations, invading exotic insects and diseases, or impacts of fire. Furthermore, examples of encouraging self-organization include leaving residual trees or other vegetation in place to let natural processes, such as facilitation and competition, sort out which trees become dominant after disturbances.

In contrast to the command and control approach (sensu Holling and Meffe 1996), CAS theory acknowledges that the complexity of components and interactions (among different hierarchical scales with non-linear and threshold patterns) leads to variable and uncertain, often non-linear behaviors. Thus, managers have to accept and anticipate an envelope of possible

TABLE 1. Descriptions of five concepts relevant to managing forests as complex adaptive systems.

Concept 1: The Dog and the Frisbee Andrew Haldane and Vasileios Madouros, working for the Bank of England, gave a talk at an economic policy symposium in Wyoming in 2012 entitled "The dog and the frisbee" (Haldane and Madouros 2012). They suggested that complex systems like the global financial system—or in our case the forest management sector—do not necessarily require complex decision making or guidelines to function. They use the act of catching a frisbee as an example of a complex problem. Predicting specifically where the frisbee will land requires extensive (complex) calculations using information about the frisbee's speed, rotation, direction, shape, and weight, as well as information about wind direction and speed, and the application of Newton's Law of Gravity. Of course, dogs do not make such calculations. Instead, they follow a simple guideline: move in a direction and at a speed that keeps the angle of gaze to the frisbee constant. Our proposed approach follows the same strategy: that simple guidelines may be adequate for managing complex systems. Even more so, simple guidelines may be preferable, as the less is more approach allows foresters to accommodate management opportunities and constraints specific to their local situation.
Concept 2: Cross-scale Hierarchical Interactions Ecosystems can be described at different, nested or hierarchical scales (Levin 1992, Sole and Bascompte 2006). Time scales are fairly straightforward, with typical values ranging from less than a second (e.g., the trap mechanism of Venus flytraps *Dionaea muscipula*) to evolutionary time scales covering billions of years. Similarly, spatial scales range from small areas (e.g., safe sites for seeds) to global scales. Other dimensions include organizational scales, ranging from genomes to cells, organisms, populations, and ecosystems (Conrad 1983). Managing forests as complex adaptive systems emphasizes that biological processes cross scale boundaries and simultaneously operate at different time and spatial scales while impacting different organizational scales (Soranno et al. 2014). Encouraging ecosystem structures and compositions that encourage processes at a wide variety of scales facilitates such cross-scale hierarchical interactions. For example, compared to even-aged, single species stands, uneven-aged mixed species stands with variable spacing encourage more cross-scale hierarchical interactions, as they allow more interactions among trees of different species and sizes across different spatial scales and with a broader set of species (Muir et al. 2002).
Concept 3: Forests as Complex Adaptive Systems Forests are a prime example of complex adaptive systems. They are composed of many components (e.g., trees, vascular and non-vascular plants, vertebrates, insects, fungi, soil, etc.) and many processes are acting simultaneously (e.g., nutrient cycling, seed dispersion, tree mortality, decay, competition, facilitation, etc.). These components and processes interact with each other and with the external environment in many different modes and over multiple spatial, temporal, and hierarchical scales and can give rise to heterogeneous structures and nonlinear relationships. These structures and relationships are neither completely random nor entirely deterministic, but instead represent a combination of randomness and order. The interactions also contain negative and positive feedback mechanisms, which can either stabilize or destabilize ecosystems. In addtion, forest dynamics are sensitive to initial conditions and memory, especially after disturbances. Consequently, the diversity of components and subsystems nested within each other give rise to emergent properties. Lastly, forest ecosystems are open to the outside world and exchanging energy, materials and/or information with other eco- and social systems (Levin 1999, Messier et al. 2013, Filotas et al. 2014).
Concept 4: Command and Control and the Agricultural Model Command and control management approaches attempt to solve problems by either controlling the process that creates the problems or reducing the negative impact after problems have occurred. As such, this approach works well for problems that are "well-bounded, clearly defined, relatively simple, and generally linear with respect to cause and effect" (Holling and Meffe 1996). Efforts to increase production efficiency through homogenization are a prime example of this approach. For example, clearcut harvests, tree planting, pest control, and thinning operations aim to ensure fast-growing even-aged, single-species stands, with even tree spacing and trees of similar sizes and qualities (Sedjo 1999). Because of its prominence in agricultural systems, this approach has been labeled the agricultural model (Puettmann et al. 2009). During the last few decades, the limitations of this approach have received more attention (e.g., Holling and Meffe 1996), especially when it is applied to complex settings, such as natural resource management (DeFries and Nagendra 2017).

TABLE 1. *Cont.*

Concept 5: Self-organization Self-organization is considered a fundamental property of how ecosystems work (Levin 1998, Sole and Bascomte 2006). It is defined as development of complex structures and patterns in the absence of a central controller. Forest management that applies the command and control approach (sensu Holling and Meffe 1996) can be viewed as centrally controlled in this context. Such management would command the specific selection of tree genetics (e.g., genetically selected trees, provenances, and species), tree planting timing and nursery stock, tree spacing, and the amount and distribution of other vegetation. Any deviation from the desired conditions will be controlled through additional planting, weed control practices, thinnings, and pest control measures. In contrast, self-organization is driven by local interactions of ecosystem components (e.g., plants, animals, fungi, etc.). These interactions can be non-linear with thresholds and discontinuities and can be modified based on feedback loops. Thus, rather than focusing on achieving a specified condition (as in the command and control approach), development of such conditions in self-organized system is driven by the outcomes of these local interactions. Consequently, development trajectory and resulting conditions are not perfectly predictable, as these interactions are changing due to autonomous processes (e.g., natural selection) and are influenced by random events. Management practices that increase the diversity of ecosystem components and facilitate more interactions across scales can be viewed as encouraging self-organization.

outcomes and emergent ecosystem properties. Emergent properties are behaviors that cannot be explained by knowing all individual components (Mayr 1982). Changes in the approach of the US federal government to forest fire management over the course of the last century may provide a good example of the different viewpoints. The traditional view assumed control and thus predictability (Holling and Meffe 1996) and concluded that large, intensive fires could be prevented through a policy of fire suppression to the point of fire exclusion (Keane et al. 2002). This approach is now considered at least partially responsible for numerous changes, including increased fuel loading and spatial continuity at the stand scale, as well as increased homogeneity at larger scales (e.g., in watersheds, and associated impacts on the fire regime; Keane et al. 2002). The command and control approach is now being replaced by a system approach, which emphasizes more than fuel loading and focuses also on fire behavior (North et al. 2015). Just as critical, this approach acknowledges the importance of maintaining diversity across stands and unique challenges associated with each wildfire. Accordingly, it suggests that this diversity of conditions is best addressed through an associated diversity of treatments, including prescribed burning, mechanical fuel treatments, and let-burn areas (Stephens and Ruth 2005). Our management guidelines aim at encouraging a similar shift in management approach in a broader silvicultural setting.

Guidelines—Ecosystem Management Objectives and Silvicultural Practices

The silvicultural guidelines are specifically focused on three characteristics of CAS (Messier et al. 2013): the diversity and variability in composition and structure at multiple scales, cross-scale interactions, and self-organization. As an expansion of the "Golden Rule" from Holling and Meffe (1996), these guidelines can be written as outlined below.

Guideline One: Encourage a Diversity of Ecosystem Components.

This guideline is based on the notion that forests with a high species and functional diversity allow more ecosystem processes to proceed even after surprises occur. The role of diversity has been discussed extensively in the ecological literature (e.g., Wilson 1999). In terms of guideline one, the context of biodiversity-stability relationships (McCann 2000) and the insurance hypothesis (Yachi and Loreau 1999, Ives and Carpenter 2007) appear most relevant. McCann (2000) highlights the various facets of the topic, including that diversity is not the driver of stability per se and other aspects are influencing diversity-stability relationships, such as the strength of species interactions (May 1973). In regards to the insurance hypothesis, Yachi and Loreau (1999) developed their empirical relationships supporting this hypothesis by quantifying the impact of species richness on the expected temporal mean and variances of ecosystem processes, such as productivity. This

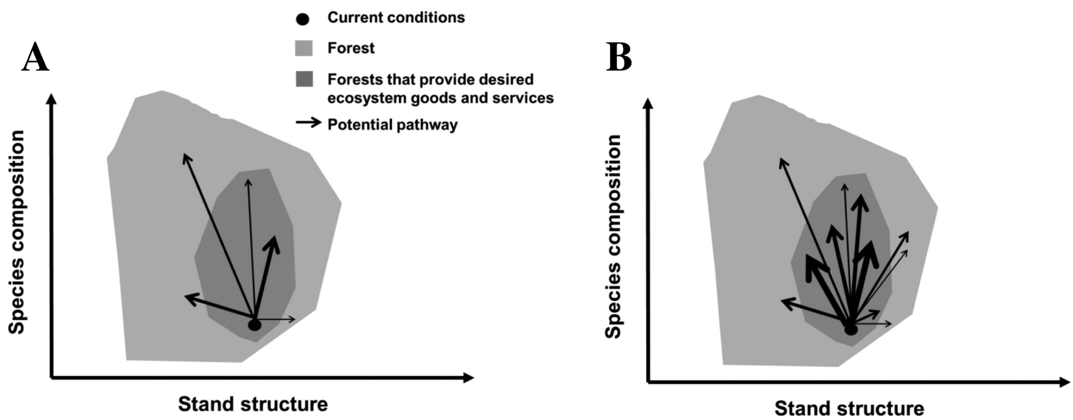

Figure 1. Forests (dot) adapt to changes in conditions (e.g., reduced rainfall, mortality due to insects or fire) through altered stand structure and composition. Potential changes are depicted as arrows, with the length of the arrow as an indicator of the amount of change and arrow thickness reflecting the likelihood that this path will be taken. Panel A shows a forest managed using the command and control approach, with limited potential pathways (e.g., by reducing species diversity through weed control). In contrast, Panel B shows a forest in which application of the three guidelines increased the amount and diversity of potential pathways. Following the guidelines will increase the likelihood that forests take a pathway that allows them to provide desired ecosystem goods and services (dark grey area) (modified from Puettmann 2014).

is especially important for landowners interested in a wider array of ecosystem services, which are supported by a variety of ecosystem processes, including maintaining adaptive capacity. With an increasingly variable and uncertain future, adaptation to changing conditions is becoming more and more important. In this context, the insurance hypothesis suggests that higher diversity in ecosystems leads to more possible developmental pathways (McKeown 2012) and thus a higher likelihood that at least one pathway will be successful at maintaining desired ecosystem services (Figure 1; Puettmann 2014).

By placing guideline one in the context of diversity and variability, we emphasize a focus beyond diversity of taxonomies, which is often expressed as species or genetic diversity. Instead, we recommend an emphasis on a diversity of functional traits, which are defined as biological characteristics important for the functioning of plants and ecosystems (McGill et al. 2006). Examples of functional traits relevant to the Pacific Northwest include tolerance of plants to drought and higher temperatures, the ability to re-sprout quickly after fires, as well as being insect pollinated, fruit producing, or a leaf chemistry that makes foliage palatable to wildlife. For example, accounting for these functional traits allowed Neill and Puettmann (2013) to demonstrate that variable density thinnings with gaps and skips or leave islands of different sizes in Douglas-fir forests increased the likelihood of maintaining food provision (for insects, songbirds, deer, and elk) in a warmer, drier climate with more disturbances. More and more information and databases have been developed that list the main functional traits of most plants (Kattge et al. 2011) or trees (Burns and Honkala 1990). Some papers have suggested grouping functional traits into key functional groups or types to facilitate management (Lavorel et al. 2007, Núñez-Florez et al. 2019).

Specifically, identifying what aspects of diversity to encourage will be relevant in preparing forests for perturbations with at least some level of predictability (Meyers and Bull 2002). For example, there is general agreement that the climate is getting warmer. Ignoring this predicted trend when encouraging specific traits or species

TABLE 2. Examples of adaptation goals and silvicultural practices recommended to address global change challenges and constraints to their implementation (modified from Puettmann [2011], as adapted from Spittlehouse and Stewart [2003], and Hemery [2008]). Constraints are labeled as economic (E), logistic (L), or informational (I).

Adaptation Goal	Recommended Silvicultural Practices	Constraints
Maintain vigorous trees by providing more resources to remaining vegetation	Thinning or removal of stressed or susceptible trees or species	Harvesting costs (E) Market availability (L)
Remove infection centers to reduce susceptibility to pests, droughts, etc.	Remove damaged or highly susceptible trees or species	Harvesting costs (E) Market availability (L) Inventory needs (L)
Ensure propagules are adapted to future climate conditions or more stressful environments	Facilitate species migration, plant seedlings/species adapted to predicted likely future environment	Seed availability (L) Lack of information about growth performance and disease susceptibility (I)
Maximize functional traits diversity in tree species to cope with biotic and abiotic future uncertainties	Facilitate regeneration and growth of existing species, or regenerate new tree species with specific traits to increase functional trait diversity	Seedling availability (L) Seeding or planting costs (E) Lack of information about functional traits (I)
Shift genetic composition to better adapted seedlings; provide tree cover in case of overstory mortality	Underplant (thinned) stands	Seedling availability (L) Seeding or planting costs (E) Lack of information (I)
Decrease risk of damage due to pest outbreaks; provide greater genetic diversity	Establish or favor mixed species or multi-provenance forest	Seedling availability (L) Planting costs (E) Logging costs (sorting) (E) Lack of information (I)
Increase flexibility to alter species or management options	Reduce rotation ages	Market availability (L)
Protect unique habitat features, e.g., riparian areas or wetlands	Leave vegetative buffers	Income expectations (E) Inventory needs (L)
Increase spatial variability in understory growing conditions and habitat	Variable density plantings or thinnings	Inventory needs (L) Planting costs (E) Harvesting costs (E)
Provide lifeboating, structural enrichment; enhance dispersal, connectivity	Green tree, snag retention, and variable patch retention (legacies)	Income expectations (E) Safety concerns (L)

may at best lead to inefficiencies, and at worst to maladaptation of the forests, and consequently to their inability to provide desired ecosystem services in the future. However, many future perturbations are relatively unpredictable (e.g., the arrival and spread of exotic diseases and insects that kill selected plant species). Thus, it is important to encourage a wide set of tree species with a high diversity of functional traits to prepare the forest for highly uncertain future perturbations. Without knowledge of which species or species groups (e.g., conifers) may be susceptible to a perturbation, increasing the number of species in order to provide a wide diversity of functional traits may be the best insurance. The maintenance or promotion of tree species with lower productivity or current value may be the insurance premium landowners have to pay to ensure that their forests will be resilient to a wide range of future perturbations. Thus, the decision as to which tree species with what set of functional traits to encourage should be made very carefully. For simplicity, in the discussion above we have emphasized trees, since that is the component foresters tend to emphasize most, but all ecosystem components (understory plants, fungi, birds, etc.) need to be considered in this context.

Guideline Two: Encourage Interactions Within and Across Hierarchical Scales.

Guideline two is based on the notion that a high diversity of interactions and feedback loops, including positive and negative feedback loops that cross hierarchical scales, will allow more ecosystem processes to proceed even after surprises occur (Sole and Bascompte 2006). In viewing forests as CAS, relevant scales include spatial and temporal scales, but also organizational scales (e.g., from gene to individual, population, ecosystem, etc.). This notion builds on guideline one, as it expands the idea of diversity beyond ecosystem components to encourage a diversity in how these components interact. As for ecosystem components, forests will benefit, in terms of adaptive capacity of the ecosystem, from a high species and functional diversity (guideline one) being set in a diversity of neighborhood conditions, stand structures, and larger scale settings (e.g., at ownership scales). Guideline two emphasizes that all these aspects need to be considered at and across multiple spatial and temporal scales with a species focus on cross-scale interactions (Levin 1992, Messier et al. 2019). The most commonly discussed aspect in this context is the diversity of tree species and associated functional traits, which directly influences how trees interact with other trees and other vegetation. For example,

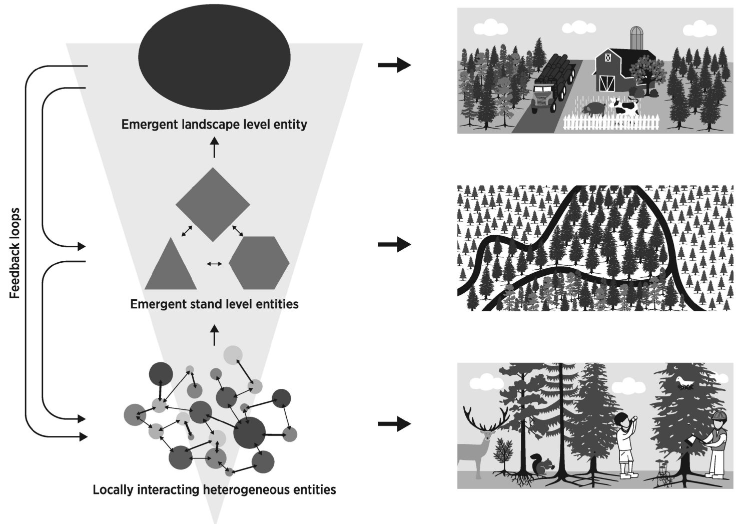

Figure 2. Conceptual model highlighting self-organization in complex adaptive systems and how local and cross-scale interactions determine neighborhood, stand, and watershed scale emergent properties that influence responses to perturbations. Modified from Messier et al. (2019).

- species traits such as water usage and shade tolerance impact plants close to the root systems (through water uptake) and further away (through shading of other vegetation; Canham et al. 1994);
- a diversity of tree ages and associated size differences will determine which plant interactions processes are prominent (O'Hara 2014);
- the importance of snags and wood debris for tree regeneration (Harmon and Franklin 1989) and as habitat for fungi, insects, and cavity nesters has been documented extensively in the PNW (Hansen et al. 1991);
- snags and fallen wood at various stages of decay influence how plants and wildlife interact at various spatial and temporal scales (Cline et al. 1980).

Guideline two stresses the importance of linking different dimensions, in this case species or functional diversity, with diversity of spatial, temporal, and organizational scales (Harmon and Franklin 1989). For example, the application of retention harvesting (Gustafsson et al. 2012) and variable density thinnings, including operations that create gaps, skips or leave islands, as well as dispersed and aggregated retention (Cissel et al. 2006), is resulting in a higher diversity of spatial patterns of tree distribution and subsequently influencing how different plants within and among species interact (Cissel et al. 2006, Puettmann et al. 2016).

Some of these aspects have been researched extensively in the PNW at the stand scale (Puettmann et al. 2016) and are being applied by various private and public landowners . However, integrating larger scales into management planning is more challenging (e.g., at regional scales; Franklin et al. 2018). Besides logistical challenges in terms of planning tools, planning at larger scales is often influenced by ownership patterns in the PNW. In contrast, larger scale planning efforts are easier in regions where single landowners have control over larger holdings (Messier et al. 2019). However, even in areas with mixed ownership, landowners can make educated guesses about management objectives of neighbors based on the neighborhood, stand, and ownership conditions. Owners can then utilize this information when designing their own silvicultural practices aimed at increasing structural diversity to encourage a variety of ecosystem components and interactions at large scales that include multiple ownerships (Wallin et al. 1994).

Other examples of how forest operations influence interactions across organizational scales among plants, wildlife, insects, etc. (Halaj et al. 2000), include variable tree spacing that results in a variety of types and strengths of mycorrhizal relationships and associated impact on nutrient uptake of trees (Fogel and Hunt 1983, Simard 2009). Such variability also results in a higher diversity of species germinating from seed banks, which affects multiple competitive and facilitative interactions between plants, including small seedlings and larger trees (Teste and Simard 2008, O'Hara 2014). At the same time, these local interactions influence and are influenced by larger scale interactions. For example, local conditions influence the amount and diversity of food source for herbivores. In turn, herbivory by mobile insects and large mammals influences pollen flow, seed rain, spread of fungal spores, or competitive status of plants (Stokely et al. 2018). Ignoring these interactions and not addressing that larger scale issues can override local drivers may become a major hindrance in achieving forest management goals. As an example, deer and elk herbivory in the PNW can be a major influence on tree regeneration and other vegetation (Stokely et al. 2018). In addition, other interactions can influence the impact of herbivory on seedling performance (e.g., through facilitation and competition with adjacent vegetation; Puettmann and Saunders 2001, Naaf and Wulf 2007). Thus, maintaining a diversity of interactions across scales provides ecosystems with the ability to follow multiple pathways and increases the likelihood that ecosystems will adapt to new conditions, while at the same time provide desired ecosystem services (Figure 1; Puettmann 2014).

Guideline Three: Encourage Ecosystem Adaptation (Self-Organization)

Complex adaptive systems are driven by self-organization (Rammel et al. 2007); "the adaptive landscape of one actor heaves and deforms as the other actors make their own adaptive moves" (Kauffman, 1993). Consequently, managing forests as CAS has a goal not to simply emphasize diversity (guideline one) and interactions (guideline two), but also to provide a focus on diversity and interactions that specifically encourages the self-organization of ecosystems (guideline three). In this context, ecosystems can follow (or explore) multiple potential pathways (Figure 1A), and applying guideline three to encourage more potential development options (Figure 1B) better allows local interactions and feedback loops to determine the pathway most suited to current conditions. The focus on encouraging self-organizing processes in guideline three is in stark contrast to the command and control approach (Holling and Meffe 1996), where management practices are concentrated on directly influencing selected ecosystem processes, such as determining which tree species will dominate through planting and weed control, and the intensity of tree interactions through planting spacing and thinnings. Thus guideline three emphasizes the principles underlying the concept of bioautomation (Puettmann and Ammer 2007) as used in the discussion of close-to-nature forestry. In this context, guideline three emphasizes integrating natural processes into management approaches to reduce intervention intensities (Lust et al. 2000).

Encouraging self-organization through a higher diversity of components (guideline one) and interactions (guideline two) has been shown to be especially influential during the stand initiation stage (sensu Oliver and Larson 1996), when vegetation responds to and/or recovers after disturbances (Puettmann 2014). Gunderson and Holling (2002) view this phase as a creative period, with high variability and many possible options for future developments, when different and perhaps novel species combinations may appear. During this time, even random, low-intensity local events, such as an early or late frost or damage where deer or elk bed down at night, may determine which species combinations become dominant over time, suggesting that stochastic events lead to high unpredictability. Once adaptive processes have acted out, later successional developmental stages have fewer developmental options (e.g., the stem exclusion phase sensu Oliver and Larson 1996). However, applying guideline three will increase the number of potential pathways even during these developmental stages and thus increase the likelihood that forests will provide desired ecosystem goods and services in the future (Figure 1).

Legacy trees left after harvest, or other legacy elements within stands or in adjacent areas, can be used to highlight guideline three. Traditionally, the number, type, and patterns of legacy trees or other legacy elements, such as downed wood or patches of dense shrub cover left behind after harvesting, were mostly viewed in terms of their life-boating impacts by providing habitat elements for selected species after harvesting, such as nesting platforms for owls (Rosenvald and Lohmus 2008). In contrast, guideline three emphasizes an additional role of legacy elements: their influence in determining ecosystem development and the number and selection of future pathways (e.g., by providing seed or shade to accelerate or decelerate tree regeneration; Keeton and Franklin 2005).

The influence of legacy trees can also provide an example how the three guidelines interact. If selected with a purpose to encourage self-organization (guideline three), a diversity of legacy trees (guideline one) within and adjacent to a particular stand (guideline two) can influence potential future pathways (Gunderson and Holling 2002, Drever et al. 2006). Specifically, which tree species are left behind will determine the composition of natural regeneration. The location where trees are retained will influence which species are likely to provide more seed rain in different parts of the forests. At the same time, the density of legacy trees will determine light, nutrient, and micro-environmental conditions for tree regeneration, understory vegetation, wildlife, and other ecosystem processes, such as wood decay. All of these factors interact and are subject to a range of random events, from small scale events, such as herbivory, to larger scale events, such as frosts or droughts. Thus, the self-organization is driven by the legacy trees in conjunction other ecosystem components and the stochastic interactions.

Application—Implementing the Guidelines

The following examples highlight selected silvicultural settings and practices as they relate to the three guidelines. The individual guidelines cannot be viewed in isolation and all practices will address multiple guidelines. We only list the most obvious linkages by referring to the guideline numbers below. In the spirit of "The dog and the frisbee" analogy, the guidelines are purposely general and aimed to provide flexibility so that they can be adapted to a variety of ecological, social, and economic situations. After discussing guideline implementation in terms of management efficiency, we describe opportunities to prepare forests for global change by 1) altering regeneration practices, 2) using species functional traits for selection of crop trees and management of other vegetation, and 3) managing tree densities and spatial layout.

The guidelines can be viewed as an overhaul of the goal to obtain optimal management efficiency through homogenization (the agricultural model; Puettmann et al. 2009), to include a higher diversity of ecosystem components and interactions, especially in regards to self-organization. For implementation of the guidelines, it may be most efficient (least costly) to pursue opportunities that result from unsuccessful applications of traditional forest management practices, such as areas in plantations with seedling mortality. In the context of managing for adaptive capacity, these areas would not be viewed as failures that need to be corrected. Such areas will likely be occupied by other vegetation and/or naturally regenerated trees (Puettmann and Berger 2006), and thus would provide for diversity of plants (guideline one) and associated processes and interactions (guideline two) in otherwise homogenous stands. Leaving these areas alone so they can self-organize following natural trends (guideline three) may not be an expense at all, when considering the additional planting and weed control costs and the lower likelihood that the replanted trees will become high value crop trees (Puettmann and Tappeiner 2014). Even at such small scales, delayed or variable reforestation success may provide for rare and thus especially valuable high-quality early seral habitats (Swanson et al. 2011, Franklin et al. 2018; guidelines one and two). The argument to deemphasize homogenization scales up to the stand scale as well. Traditional forestry operations aim to homogenize forests by applying similar reforestation standards to multiple stands. In practice, a common standard can result in intensive and expensive efforts in few, selected stands where homogenization is logistically expensive. This could require repeated weed control and plantings to restock stands that for one reason or another fail to achieve the regional minimum stocking standards. Instead, it may be more profitable to give up attempts to achieve these standards on the few, most problematic stands. Despite or because of these regeneration problems, these stands add diversity and can provide important ecosystem services other than timber production, including larger scale connections (Messier et al. 2019) that increase the adaptive capacity of the forested region (guidelines one, two, and three).

Management practices that maintain or increase tree species diversity have a long history in forestry (e.g., Gayer 1886, Pretzsch et al. 2017). This topic has received increased attention in the last few decades in the western Douglas-fir region of the PNW as well (Wierman and Oliver 1979, Puettmann et al. 1992). Initially most of the interest in mixed species was viewed in a command and control approach, with a search for optimal species mixtures and spacings for increased growth and yield (Binkley 1983, Amoroso and Turnblom 2006, Erickson et al. 2009). In this context, increased evidence of diseases, such as Swiss needle cast (caused by *Phaeocryptopus gaeumannii;* Filip et al. 2000) and black stain root disease (caused by *Verticicladiella wageneri*; Hansen and Goheen 1988) that preferentially damage Douglas-fir, has led to a greater interest in tree species not affected by these diseases. At the same time, this can be viewed as an application of guideline one, where foresters specifically consider traits that relate to a species' ability to respond to disturbances. This guideline can be applied by either choosing a specific combination of crop tree species or by allowing crop and non-crop tree species to establish and grow in managed stands without interference (guideline 3). As an example of the former, mixed red alder (*Alnus rubra*)/Douglas-fir stands have been planted in the western portion of the PNW as part of a research study (e.g., Radosevich et al. 2006). More frequently red alder has regenerated naturally in Douglas-fir plantations due to limited or ineffective weed control, and because it could take advantage of its fast initial growth, often developed into a significant stand component (guideline three; Puettmann et al. 1992) with (in some cases) substantial economic value (Haight 1993). Similarly, combinations of mixed red alder/Sitka spruce (*Picea sitchensis*) and combinations of Douglas-fir, western hemlock (*Tsuga heterophylla*), and red alder are quite common in selected parts of the region (Himes and Puettmann, in press). Tree species diversity can be encouraged when planning weed control practices by choosing the location and timing of herbicide application, or providing guidance for manual weed control, or when carrying out precommercial thinning operations to allow natural processes to sort out species mixtures in selected places (guideline three). Alternatively, other species, such as bigleaf maple (*Acer macrophyllum*) and Oregon white oak (*Quercus garryana*), may also provide the desired trait diversity, even though these mixtures can lead to reduced harvest values depending on differential growth rates, harvest costs, and log prices. Again, it is the diversity in traits that is important (guideline one). For example, in contrast to most conifers, hardwood trees sprout after fires and thus ensure that several ecosystem processes (e.g., carbon sequestration, water and nutrient cycling, soil stabilization, and mycorrhizal relationships) will continue immediately after the disturbance even before any management treatment shows impacts. Similarly, guideline one suggests that species selection should avoid mixing species that are attacked by the same insect or fungi, such as mixtures of Douglas-fir and true firs (*Abies* spp.), as both are susceptible to laminated root rot (*Phellinus weirii*). Instead, in areas with high risk of laminated root rot, mixtures of Douglas-fir with non-susceptible species such as red alder or western redcedar (*Thuja plicata*) may be more appropriate (Childs 1970). Also, guideline one encourages mixtures of species that differ in their susceptibility to other natural disturbances. For example, compared to conifers, hardwood species are less likely to suffer wind damage during winter storms but may be more susceptible to ice storms (Priebe 2016).

Several benefits of mixed tree species forests can be accommodated by allowing or encouraging diverse and vigorous companion vegetation during various phases of forest development (Swanson et al. 2011, Donato et al. 2012, Puettmann et al. 2016). Specifically, sprouting shrubs and species with a long-lived seedbank may also ensure that ecosystem processes continue or are initiated again immediately after a disturbance (guideline three; Yelenik et al. 2013). However, the benefits in terms of resilience and self-organization have to be weighed against the economic costs, as areas with limited or no weed control may result in delayed regeneration after harvesting operations (Rose et al. 2006) and intensive disturbances (Shatford et al. 2007). Rather than applying the guidelines across the board, potential financial losses may be minimized when they are applied only to smaller portions of stands or ownerships (guideline two), especially when these portions are selected with economic considerations in mind (e.g., areas with a steep slope or with access problems due to stream crossings).

Once the crop trees are established, the wide range of stand densities that produce similar stand growth in Douglas-fir (Marshall and Curtis 2002) provide flexibility for forest managers. Thus, overstory densities that are sufficiently low to allow for the establishment and growth of a diverse and vigorous understory of strongly interacting species with a variety of functional traits (guidelines one and two) (Ares et al. 2010), including regeneration of some tree species (guideline three) (Kuehne and Puettmann 2008, Dodson et al. 2014), may not necessarily result in significant growth loss of overstory trees, especially when only a portion of the stands have this lower density (guideline two) (Dodson et al. 2012). Also, higher intensity thinnings help avoid or at least reduce the costs associated with the need for repeated thinning operations. At the same time, low tree densities may lead to temporarily understocked conditions that may provide for diversity hotspots to develop and thus encourage self-organization (guideline three). Similarly, including gaps or small areas that are purposely understocked (guideline two) (Cissel et al. 2006) may actually increase the profitability of thinning operations due to the higher harvest volume of larger trees. This is especially effective when the application of guideline two, through the spatial layout not only of gaps and low stocked areas but also of leave islands, is driven by current stand conditions. Leave islands can be placed in areas with high water tables, rocky outcrops, or low value trees. At the same time, harvesting operations become more profitable when the spatial layout of silvicultural prescription accommodates harvesting logistics (e.g., gap locations are linked to layout of skid trails or cable corridors).

In the same context, creating a variety of safe site or seedbed conditions during harvesting or site preparation can also encourage the regeneration of a diversity of species (guidelines one and three). For example, decaying nurse logs can provide conditions that allow selected species to establish (e.g., western hemlock and Sitka spruce in wetter riparian areas) (Harmon and Franklin 1989, Pabst and Spies 1999). Similarly, gaps and stand edges may provide suitable conditions for regeneration of a variety of tree species (Gray and Spies 1997) and other vegetation (guideline two) (Fahey and Puettmann 2008). Again, taking advantage of existing variability in soil and vegetation conditions when laying out silvicultural treatments may lead to lower economic losses compared to stands managed for maximum profitability.

Assisted migration can be viewed as an example of a command and control (Williams and Dumroese 2013). In contrast, managers following the guidelines also would encourage opportunities for natural migration (guideline two). For example, facilitating natural regeneration of a variety of species by leaving residual trees as biological legacies, and/or using site preparation techniques that encourage natural spread and create a variety of safe-site conditions may establish migration corridors (guidelines one, two, and three). Thus, our guidelines encourage assisting natural migration (Messier et al. 2019).

A good example of migration assistance can be seen in the role played by areas that either did not burn or were not severely burned during a fire. Surviving trees in these areas can then influence the amount, speed, and diversity of natural tree regeneration in areas with burns that lead to high tree mortality (Ooi et al. 2006). Similarly, harvest operations can act as encouraging diversity (leave multiple species; guideline one) to encourage natural development through self-organization (guideline three) in strategically selected places, taking interactions across spatial and temporal scales into account (guideline two).

We conclude with our assertion that the generality of the guidelines is an important feature. By using these three simple guidelines, foresters should be able to manage in the context of global change (in other words to "catch the frisbee"). However, rather than strictly following rules or regulations, the guidelines require foresters to develop and pursue specific opportunities for implementation suitable for their specific situations. More importantly, the inherent flexibility by providing general guidelines also recognizes that adaptation is often only one of many goals for forest managers. In fact, other goals typically drive forest management decisions, such as provision of income, hunting, or wildlife viewing opportunities. The guidelines were developed to accommodate such goals efficiently, while providing a filter to ensure that forest ecosystems are better able to adapt to the variety of surprises that are expected under global change.

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