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Silviculture in an uncertain world: utilizing multi-aged management systems to integrate disturbance†

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Forest management faces an uncertain future with changing climates and disturbance regimes. Multi-aged forest management systems represent a promising approach for increasing resistance and resilience, thereby limiting major disruptions to timber production and other ecosystem services. Multi-aged stands inherently have greater resistance and resilience to disturbances because of the presence of several age classes and more potential pathways for post-disturbance management and recovery. The preponderance of research also indicates few differences in productivity between multi-aged and even-aged management strategies. These factors combined suggest that increased adoption of multi-aged management systems will lead to a reduction in long-term risks. We advocate a disturbance integration management strategy that encourages managers to emulate disturbance effects with management, anticipate disturbances in planning, integrate the management of residual stand structures into salvage operations and build variable treatment intervals or cutting cycles into management regimes.

Introduction

Forest disturbances were historically viewed as rare perturbations with a low level of predictability and of little value either ecologically or socially (Pickett and White, 1985; Botkin, 1990; Attiwill, 1994; Oliver and Larson, 1996; Marris, 2011). In recent decades, an emerging recognition of the ecological value of disturbances has placed disturbances in the forefront of many forest-based ecological studies (White and Jentsch, 2001; Turner, 2010; Mori, 2011; Romme *et al*., 2011; Mitchell, 2013). This is due, in part, to a general increasing awareness of the commonality and frequency of disturbances, and the importance of disturbances in affecting forest structure, forest development and other forest processes. This has culminated in an effort to reframe silvicultural activities as forms of disturbance emulation that direct stands on trajectories that maintain or restore ecosystem processes and biological diversity. There is an emerging body of literature on emulation of natural disturbance regimes with forest management (Attiwill, 1994; Franklin *et al*., 2002; Harvey *et al*., 2002; Seymour *et al*. 2002; Perera *et al*., 2004; Drever *et al*., 2006; North and Keeton, 2008; Long, 2009; Geldenhuys, 2010). Disturbances are emulated in a number of ways, ranging from actually integrating forms of a particular disturbance into management regimes (e.g. prescribed burning) to designing harvest treatments that leave residual structures similar to those resulting from natural disturbances (Kohm and Franklin, 1997; Beese *et al*., 2003).

Although disturbances are now recognized as important ecological phenomena, they are still viewed as major economic threats that can rapidly destroy the value of forest investments. A critical element in the development of modern forest management has been the management of disturbance-related risks and reduction of the uncertainty associated with these risks. Disturbance risks are mitigated through a variety of means including prevention, control of disturbance agents such as insects or pathogens, and distribution of investments across large land areas to spread risk beyond the boundaries of any single disturbance event (Kangas and Kangas, 2004; Barbour *et al*., 2005; Hanewinkel *et al*., 2010; Keskitalo, 2011; Yousefpour *et al*., 2011).

Across some spatial and temporal scales, disturbances exhibit a certain degree of predictability (i.e. a disturbance *regime*; White and Pickett, 1985; Agee, 1993; Turner *et al*., 2001; Frelich, 2002; Suffling and Perera, 2004). However, characterization of such trends necessarily relies on retrospective analyses that may not accurately represent future probabilities. Many ecosystems are currently experiencing rapid changes, and many of these changes are interacting with natural disturbances. Ecological shifts that may affect disturbance regimes are numerous and diverse, ranging from species invasions to climate change to past anthropogenic suppression of natural disturbances. Thus, disturbance-related risks are likely to become increasingly important and less predictable in the coming decades (Dale *et al*., 2001; Bodin and Wiman, 2007; Keskitalo, 2011; Mori, 2011; Yousefpour *et al*., 2011).

Multi-aged stand management provides the tools and flexibility to integrate partial disturbances into management regimes. Multi-aged stands include two or more age classes or cohorts (Helms, 1998) and are a result of repeated disturbances or silvicultural interventions that regenerate these new age classes (O'Hara, 1998). They can be highly variable, ranging from a few residual older trees to complex mixtures of species and age classes. As a management alternative to plantations or other forms of even-aged management, multi-aged silviculture is drawing increased interest worldwide (Spiecker, 2003; Mizunaga *et al*., 2010; Diaci *et al*., 2011). The confluence of expanded applications of multi-aged systems and greater use of silviculture to emulate disturbances creates opportunities for greater use and expanded views of multi-aged silviculture.

In this paper, we discuss the advantages of multi-aged systems in disturbance-prone environments. Multi-aged stands offer forms of resistance and resilience not generally present in even-aged stands and may be appropriate for a wide variety of ownerships. Specifically, multi-aged stands generally exhibit productivity that is comparable with even-aged systems, greater resistance to disturbances, better maintenance of ecosystem processes when disturbed and faster post-disturbance recovery. A key feature of our argument is that multi-aged management approaches offer an effective means to integrate and absorb partial disturbances into management regimes, thereby reducing the disturbance-related risks normally associated with managed forests.

Forest disturbances

Disturbances are highly variable even within a single forest type. These may include wind, fire, insect and pathogen effects, flooding, ice storms, hail storms, landslides and many others. The disturbances for a given forest type are often described with a disturbance regime, typically including characteristics such as the type, frequency, duration, severity, size and spatial pattern (White and Pickett, 1985; Agee, 1993; Turner *et al*., 1998; Frelich, 2002; Suffling and Perera, 2004). The disturbance regime therefore provides information necessary to understand the formation and subsequent development of the stand that follows the disturbance. The stand interacts with the disturbance regime by varying over time in its susceptibility to disturbance. Longer intervals between disturbances generally result in increased susceptibility (Oliver and Larson, 1996). Disturbance regimes are often represented with averages or ranges that describe return intervals, severity or timing (Baker and Ehle, 2001). But these regimes are highly variable over time, with great variation around means, and may also have highly variable spatial effects even over relatively small scales (North, 2012).

Many disturbances lead to multi-aged stands. In these cases, a significant proportion of the disturbed stand survives the disturbance, forming stand structures that are much more complex than those that result from stand-replacing disturbances. In some cases, with repeated partial disturbances, many age classes may ultimately form, resulting in very high stand complexity. These age classes may be spatially dispersed and often form few if any recognizable patterns. Irregular age structures of multi-aged stands have been observed in many forest types (e.g. Hett and Loucks, 1976; Lorimer, 1980; White, 1985; Oliver and Larson, 1996; Lorimer *et al*., 2009).

Forest management on different ownerships

Several authors have classified forest landscapes into one of three types based on management objectives (Salwasser, 1990; Seymour and Hunter, 1992). One type, 'production forests', involves lands managed for commodity production, primarily timber. Another type consists of 'preservation lands' managed as parks and wilderness, and where no active management or commodity production occurs. The third type is 'multiple benefit lands', where forests are managed to produce a wide variety of benefits or ecosystem services such as recreation, wildlife habitat, water and timber.

These three types have different approaches to risk, and particularly to risk of disturbances. Production forests are managed to provide a consistent production of timber products over time. Risk is reduced by shortening rotation lengths, altering stand structure or adjusting the stocking or amount of wood in the forest. These younger and lower density forests are often more resistant to insects, have less fuels and include more highly developed road systems. When disturbances do occur, a typical strategy is to salvage the timber of value, quickly reset the management cycle and return the affected areas to production. The road systems aid reduction in disturbance severity (for example, through fire suppression) or salvage. This is a traditional strategy characteristic of fully regulated forests – where a sustainable level of wood production is achieved through consistent harvest levels or area treated – that is concerned with both timber production and risk reduction (Salwasser, 1990; Seymour and Hunter, 1992).

Preservation forests are managed with a more ambivalent approach towards risk from disturbance. Because these lands are often managed to maintain ecological integrity, natural disturbances are not generally viewed as problematic. Risk from disturbances is tolerated, as are the effects of disturbances on the landscape. However, there may be efforts to minimize risks to areas beyond the reserve boundary from disturbances that occur within the boundary (e.g. prescribed burning to reduce future wildfire intensity, which may reduce the likelihood that such wildfires will spread onto neighbouring lands as well as lessen smoke-related health effects in nearby communities). Overall, management activities in preservation forests have been motivated primarily by objectives related to the maintenance of landscapes within some semblance of their historical range of variation, with the reduction of risk being a secondary objective (Salwasser, 1990; Seymour and Hunter, 1992).

Multiple benefit lands are often actively managed to reduce risk of disturbance. This segment of the forest landscape is often large and the many multiple uses may not be compatible with disturbances that disrupt human forest uses, damage investments or have undesirable effects on ecosystem services or structures. Additionally, some of the disturbance-related effects of timber management – an anthropogenic disturbance – are incompatible with other uses. Because of the many uses, and the extent of their dispersion across forested landscapes, much of the multiple benefit forest is used primarily for non-timber resources. These forests may not be regulated in the traditional sense of consistent wood extracted or area harvested. Instead, management may focus on consistent production of other ecosystem services (O'Hara *et al*., 1994; Franklin *et al*., 2007; Franklin and Johnson, 2012). Management may attempt to reduce risk of disturbances through removals of dead or unhealthy trees, prescribed burning or density management that, for example, increases stability of residual trees (Wilson and Oliver, 2000; Wonn and O'Hara, 2001).

Manipulation of stand structures on multiple benefit lands may be to facilitate non-timber objectives such as enhancement of aesthetics or provision of wildlife habitat. Complex stand structures, featuring mixed species and multiple age classes, are becoming increasingly common on these lands. Multi-aged stocking procedures (e.g. O'Hara and Gersonde, 2004) are used to control stand structure. However, these procedures are often oriented towards producing stands with regulated structures: structures that are controlled by distributions of tree sizes or relatively uniform distributions of tree age classes (O'Hara, 1998). Hence, they tend to promote idealized representations of disturbance effects, emulating average disturbance effects but not necessarily the full range of natural variation; as a result, even with high stand-level complexity, landscape-level heterogeneity may remain low. These multiple benefit lands therefore represent places where disturbance effects may loosely guide management, but where risks from stochastic disturbances are intentionally reduced. Concepts of disturbance integration are most applicable to these multiple benefit lands.

Justification for disturbance integration

Multi-aged stands that are to successfully integrate disturbance must exhibit both resistance and resilience to such perturbations. Following Millar *et al.* (2007), we define *resistance* as the ability to avoid or prevent disturbance impacts and *resilience* as the capacity to allow some change but return to pre-disturbance conditions. On an individual tree basis, examples of resistance include the ability to survive low-intensity fire, withstand high winds and successfully fight off insect attack, while examples of resilience include post-disturbance basal sprouting and re-iteration of broken leaders. At the stand level, resistance can emerge even if many individuals succumb to disturbance, and resilience encompasses all forms of post-disturbance regeneration. For instance, a stand that experiences 100 per cent mortality (of both boles and root systems) could still qualify as highly resilient if sufficient post-disturbance regeneration occurs (e.g. release of seeds from serotinous cones following stand-replacing fire; Ramage *et al*., 2010). Also note that the terms 'resistance' and 'resilience' are not confined to individual species; they can refer to genotypes, functional groups and stand structures. Precise operational interpretations of these concepts will be highly dependent upon management objectives.

For multi-aged management to be a realistic option, productivity must also be comparable with even-aged stands. Thus, before elaborating on resistance and resilience in multi-aged stands, we first provide a brief overview of this topic. The relative productivity of multi-aged and even-aged stands has been a point of debate for many decades. Previous studies have included empirical comparisons (Assmann, 1970; Smith and DeBald, 1978; Guldin and Baker, 1988; Laiho *et al*., 2011), modelling projections (Hasse and Ek, 1981; Haight and Monserud, 1990; Tahvonen 2009), economic analyses (Haight, 1987; Haight and Monserud, 1990; Hanewinkel, 2002), comparisons of large-scale forest inventory data (Lähde *et al*., 1994a, b; Long and Shaw, 2010), functional comparisons (O'Hara and Nagel, 2006) and reviews (Kuuluvainen *et al*., 2012). There are studies that report even-aged alternatives as more productive and others that indicate multi-aged are more productive. The emerging consensus is that there may be some advantages in terms of both productivity and economic return associated with multi-aged stands, but there is often little if any significant difference in inherent productivity between these two management strategies that can be generalized over all forests and variations in management. O'Hara and Nagel (2006) concluded that whereas differences in productivity may exist, they were probably insignificant compared with the great range of structures included in these two broad management approaches. Operational differences do exist, however, and these may provide unique advantages to even-aged systems to enhance production in ways that are not generally possible in multi-aged stands. However, on multiple benefit lands, the relative inherent productivity cannot be cited as a justification for discriminating against multi-aged systems.

The inclusion of multiple tree species can further enhance structural complexity of multi-aged stands while also providing the additional benefits resulting from compositional diversity (e.g. reduced stand-level susceptibility to species-specific insects and pathogens, possible productivity gains resulting from complementary resource use and greater production of ecosystem services; Gamfeldt *et al*., 2013). While structural and compositional diversity can be evaluated in isolation, these two sources of diversity are unavoidably intertwined. Because tree species vary in their environmental niches (e.g. light and moisture optima), structurally complex multi-aged stands can support a greater diversity of species than even-aged stands with uniform environments. Thus, the increased potential for diverse species assemblages can itself be seen as an advantage of multi-aged management, and a discussion of multi-aged stands would not be complete without considering the inclusion of multiple tree species.

If multi-aged stands are less susceptible to disturbance, this also implies that multi-aged stands might be better at long-term carbon sequestration. It has been argued that 'carbon is managed better with a number of smaller interventions than a few large removals' (Swift, 2012). Likewise, the series of small but frequent disturbances that result in multi-aged stands may release less carbon than less frequent but stand-replacing disturbances. Corresponding to higher average stocking in multi-aged stands over a series of cutting cycles (O'Hara and Nagel, 2006), multi-aged stands may store greater amounts of carbon than comparable even-aged stands (D'Amato *et al*., 2011a). The inherent retention of continuous structure in multi-aged systems results in greater average storage given comparable assumptions.

Resistance of multi-aged stands

Multi-aged stands form complex structures with multiple age classes and canopy strata. The primary resistance of multi-aged stands is their range of tree ages and sizes and the likelihood that a diverse stand structure has a diversity of means to resist most disturbance events (Figure 1; Drever *et al*., 2006; Bodin and Wiman, 2007; Millar *et al*., 2007; Swift, 2012). The spatial heterogeneity of multi-aged stands is also a component of their resistance. When partial disturbances leave residual structural features, the resultant multi-aged stands not only retain some structure but also they maintain many pre-disturbance functions.

Complex multi-aged structures provide resistance to a number of disturbance agents, both abiotic and biotic. As an example of the former, there appear to be advantages for multi-aged stands in

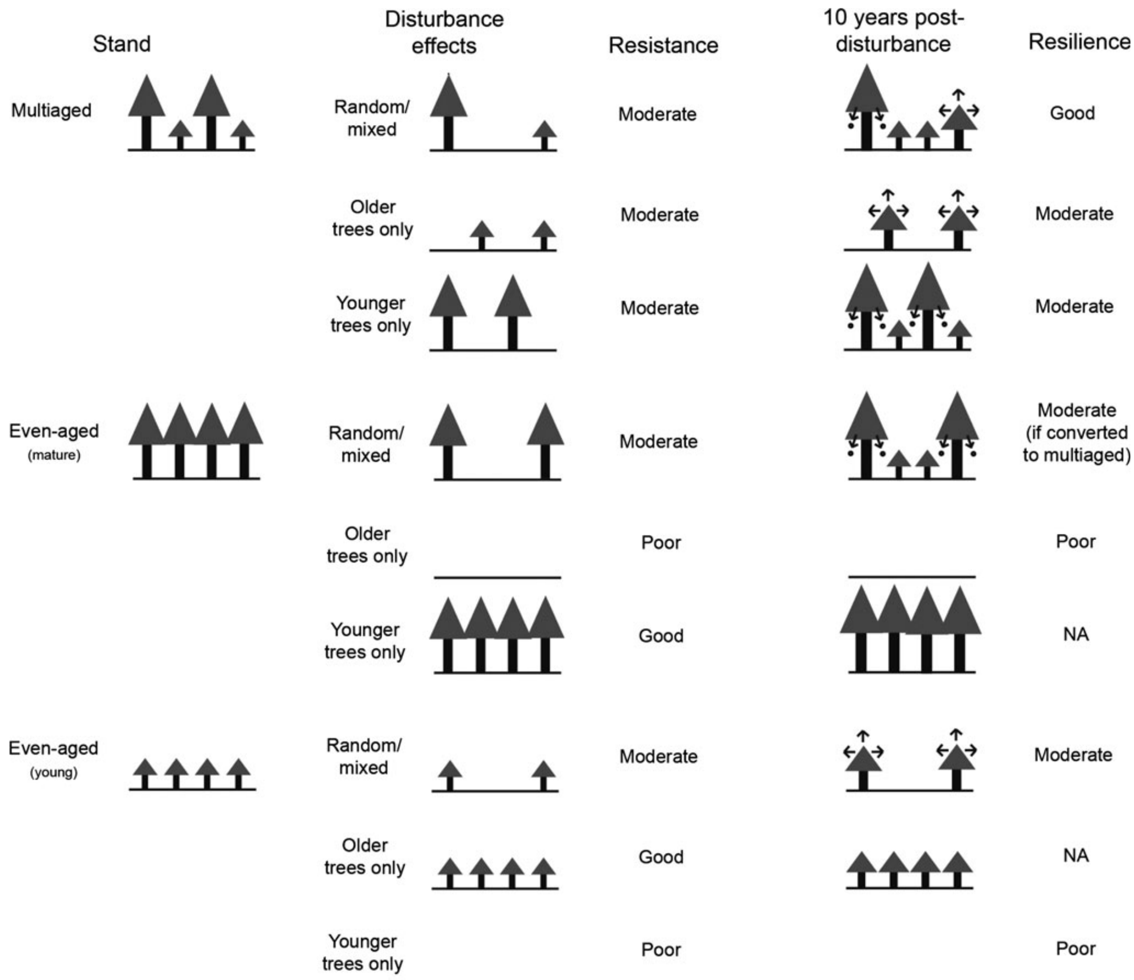

Figure 1 Hypothesized differences in resistance and resilience between multi-aged and even-aged stands. The species represented is (1) dispersal-limited, (2) characterized by poor seed production when young, and (3) better able to respond to increased resources (e.g. due to disturbance) when young. Disturbances with the potential to be more severe in multi-aged stands (e.g. dwarf mistletoe outbreaks) are assumed to be rare or non-existent in this ecosystem.

avoiding wind damage (Bodin and Wiman, 2007; Stanturf *et al*., 2007; Beach *et al*., 2010). Trees may become more resistant to wind stress because they endure greater exposure to wind in structurally diverse canopies. There is evidence from both simulations (Mason, 2002) and long-term plot data (Kuhn *et al*., in review), as well as previous reviews (Everham and Brokaw, 1996; Mitchell, 2013), that multi-aged stands have less wind damage than even-aged stands. However, mechanistic wind damage models have not shown an effect (Gardiner *et al*., 2005), possibly because they typically focus on mean tree effects and not the structural diversity of more complex forests (Gardiner *et al*., 2008). Forests of multi-aged stands would have fewer abrupt stand edges, which are particularly vulnerable to wind damage. Additionally, the changes in structure during periodic treatments of multi-aged stands are lighter and thus also reduce the sudden changes in structure associated with considerable wind damage (Gardiner *et al*., 2005). Ice storms represent another important abiotic disturbance agent: understorey trees in multi-aged stands may also be protected by overstorey trees, providing a form of resistance (Bragg *et al*., 2003).

In some instances, multi-aged stands may be less resistant to disturbance and thus the potential benefits of multi-aged systems need to be evaluated separately for each managed forest. For instance, in fire-prone environments, multi-aged stands may pose greater risks because of continuous vertical fuel ladders. However, fire-prone environments are often on drier sites where densities need to be controlled, and often these reductions in density can alleviate fuel and fuel-continuity issues. In addition, the openings created by selection treatments that create gaps or otherwise provide breaks in canopy continuity might also inhibit crown fire spread (Moghaddas *et al*., 2010).

The relationships between stand structure and biotic disturbance agents are more complicated. However, opportunities for management to improve resistance are significant. There are insects and pathogens such as mountain pine beetle (*Dendroctonus ponderosae*) that successfully attack trees over a threshold size, thus making the rest of the stand resistant. Alternatively, there are biotic agents such as dwarf mistletoes (*Arceuthobium* spp.) that spread easily in multistrata stands. Resistance to biotic agents is generally enhanced with tree species diversity because these agents are often species-specific (Edmonds *et al*., 2005). Mixed-species, multi-aged stands therefore offer additional levels of resistance because so many insects and pathogens are species-specific.

Multi-aged stand management also serves as a means to mimic, or even replace, disturbances. Removal of individual trees or groups of trees can emulate the effects of insects and pathogens on the forest canopy. These treatments can target trees and clumps of trees more susceptible to disturbance, effectively replacing natural disturbance events with strategic timber removal that may or may not correspond to existing stand delineations (O'Hara and Nagel, 2014). Additionally, when combined with management efforts to maintain lower stand densities or alter species composition, these management treatments provide for more resistant stands.

Resilience of multi-aged stands

Many of the resilience of multi-aged stands arises directly from their resistance. Residual stand components provide existing structure and maintain some functions of the pre-disturbance stand. Many of these structures and functions enhance growth and regeneration, thereby facilitating recovery to a pre-disturbance state (Figure 1). Multi-aged stands are also likely to exhibit resilience that is not directly linked to resistance. Thus, even if multi-aged and even-aged stands exhibit comparable resistance (e.g. equivalent proportional mortality across all age classes), multi-aged stands may still be advantageous in disturbed forests. Provided that disturbance-induced mortality is not severely biased towards particular age or size classes, residual post-disturbance elements will be more diverse in multi-aged stands than in even-aged stands. This variation in residual age and size classes enables a broader range of recovery mechanisms. For instance, younger trees often exhibit greater plasticity (e.g. adventitious sprouting, rapid response to increased light) and greater potential to recover from wind or snow damage, while older trees have the capacity for greater seed production (Oliver and Larson, 1996).

In stands with greater tree species diversity, resilience is likely to be further enhanced. Different species have different responses to disturbance, and the species that is most successful post-disturbance (in terms of establishment and/or growth) will depend not only on the disturbance type, but also on other stochastic disturbance characteristics (e.g. intensity, scale, season; White and Jentsch, 2001). Therefore, stands with high tree species diversity should be better able to respond quickly to whatever disturbance event might occur. For example, a disturbance that only affects some species in a mixed stand will leave greater structure and greater post-disturbance functionality than if a susceptible single-species stand is affected.

Permanence and risk management

As intimated above, the distinction between resistance and resilience often becomes blurry: those structural elements which provide stands with the greatest resistance – the surviving age classes – are also important for its resilience. Another way to view this is through risk management. Multi-aged stands reduce the risk of a large reduction in function. Cordonnier *et al*. (2008) referred to this as permanence, or the capacity of a system to remain within a range of satisfactory values (see also Hanewinkel *et al*., 2010). Systems, including stands, are dynamic and risk varies across states. By providing both resistance and resilience, multi-aged stands provide a range of states where risk is less than it might be for even-aged stands.

Disturbance and uncertainty

While we have thus far discussed resistance and resilience in the context of natural disturbances, these terms can also apply to management activities such as thinning treatments and timber harvest. Accordingly, managers need to evaluate forest responses to both natural disturbances and silvicultural treatments. Although such considerations are commonplace, managers often fail to thoroughly examine how resistance and resilience are affected by the *interaction* of management actions and natural disturbances (Mori, 2011), especially in multi-aged stands (except perhaps with regard to the most predictable of disturbances; e.g. low-severity windthrow events).

Major sources of uncertainty that will affect management planning in the coming decades include exotic organisms and climate change. Exotic species can affect disturbance regimes in several ways, including indirect effects on abiotic disturbances (e.g. invasive plants increasing fuel continuity and fire risk) and direct impacts of the invading species (e.g. forest pests), sometimes yielding stands that are profoundly altered in terms of structure and/or composition (Mack and D'Antonio, 1998). For example, in California's coastal forests, sudden oak death (*Phytophthora ramorum*) – much like chestnut blight (*Cryphonectria parasitica*) in eastern North America a century earlier – is causing pulses of severe mortality, dramatically affecting stand structure and probably permanently altering the relative abundances of common tree species (Ramage and O'Hara, 2010; Ramage *et al*., 2011).

Climatic changes will almost certainly alter forest disturbance regimes in the coming century (Dale *et al*., 2001; Bodin and Wiman, 2007). Fire frequencies and sizes are generally expected to increase, but predictions are variable for individual locations, and there is a great deal of uncertainty about how fire intensity and severity will be affected by climate change (Flannigan *et al*., 2009). The average intensity of major storms is predicted to increase as global temperatures rise, but again, predictions for specific regions are often highly variable (Knutson *et al*., 2010).

In addition, humans often directly manipulate disturbance regimes (e.g. fire suppression or management, flood control). These manipulations could potentially reduce disturbance-related uncertainty and risk, but only if (1) objectives remain constant for long time periods, and (2) the resulting interventions are successful. However, in practice, it is common that one or both of these conditions are not satisfied. Human tinkering has been occurring for millennia, but the specific characteristics of intervention have not remained constant and will likely continue to change. As an example of such a process, in western North America, fires were frequently ignited by Native Americans prior to European settlement but actively suppressed for most of the last century, and are now once again being utilized in some areas (Donovan and Brown, 2007). Furthermore, during periods when objectives remain relatively constant, our track record of success is mixed at best, with disturbance control efforts often leading to unanticipated problems. For instance, fire suppression and flood control efforts frequently increase the intensity and/or severity of the disturbances that eventually occur (Keeley *et al*., 2009). As a result, human efforts to rigidly control disturbance regimes often increase disturbance-related uncertainty and risk.

Management and disturbance integration

Many of the forest regulation concepts that developed in modern forest management were to ensure consistent and sustainable production of ecosystem services, particularly timber. This approach generally succeeds in periods of limited disturbance, but the structurally and compositionally uniform stands that characterize these systems are highly sensitive to disturbances, especially those disturbances that are novel or severe (Puettmann, 2011). Forests experiencing altered disturbance regimes can be viewed as novel ecosystems (*sensu* Hobbs *et al*., 2006) that are likely to exhibit unpredictable ecological trajectories and responses, and which may therefore require innovative management strategies (Seastedt *et al*., 2008). In particular, rapidly changing conditions elevate the importance of resistance and resilience, while reducing the importance of maximum productivity in disturbance-free periods (Keskitalo, 2011; Puettmann, 2011). More generally, the optimal strategy given little or no uncertainty is likely to differ from the optimal strategy given high uncertainty (Nicholson and Possingham, 2007; Beach *et al*., 2010; Hahn and Knoke, 2010; Mori, 2011).

We propose concepts for the management of forest lands to achieve a greater level of disturbance integration into silvicultural regimes. By 'disturbance integration', we refer to specific operations and approaches to emulate disturbances and integrate disturbance regimes into management. We argue that management systems that emulate natural disturbances, particularly multi-aged approaches, generally lead to forests that are more resistant and resilient to future disturbances. These concepts apply primarily to the 'multiple benefit' lands where any single ecosystem service is not dominant and where a reduction of one service is acceptable. Whereas many previous approaches to management emphasize organization of management activities to produce a certain arrangement of stand structures, we propose that these structures be both less systematically designed and arranged across multiple benefit forest landscapes. This could be described as a movement from regulated to unregulated forests or a deregulation of many of the traditional forest management concepts.

These 'irregular' management approaches allow for, and potentially contribute to, the development of multi-aged stands with complex age structures (*sensu* O'Hara, 1998). Many of the concepts related to multi-aged silviculture, and the great range of these multi-aged systems, have much to contribute to disturbance emulation. However, multi-aged stand management strategies may not be appropriate for all landscapes. Additionally, the transformation or conversion of even-aged to multi-aged stands can be expensive and lengthy (O'Hara, 2001). We recommend that disturbances themselves be considered as opportunities to commence a conversion, possibly integrated with salvage treatments. This type of flexibility is a form of adaptability to uncertainty that leads to risk reduction (Hanewinkel *et al*., 2010).

Disturbance emulation and anticipation

Silvicultural operations can be designed and implemented in ways that emulate and anticipate disturbance regimes. Disturbances have a wide range of effects on forest stand structure, with silviculture including a range of treatments to emulate these effects. For example, thinning methods are often described by the relative canopy position of the trees that are removed or retained (Smith *et al*., 1997). 'Thinning from below' removes smaller trees, and 'thinning from above' removes larger trees. These two broad treatment types can be used to emulate different disturbances. The former may represent effects on stand structure from drought or suppression, whereas the latter may represent effects of windthrow, ice storms or some insect mortality. Variable-density thinning (Carey, 2003; O'Hara *et al*., 2012) may also be used to enhance stand-level spatial heterogeneity. Likewise, regeneration methods, such as clearcutting or seed tree methods, may emulate disturbances such as stand replacement or near-stand replacement disturbances, respectively.

Creation of gaps or group openings within stands through silvicultural treatment may also mimic and anticipate disturbance effects. These small openings emulate the effects of many disturbances such as some insect mortality, mixed severity wildfire, windthrow, some root pathogens, and others. The presence of these canopy openings, which should ideally be highly heterogeneous, promotes multi-aged stand development and provides a form of resistance and resilience to future disturbances that, in effect, anticipates future disturbance. When disturbances do occur, multi-aged stands can reduce the extent and severity of these events and help restrain them to more natural limits.

Salvage operations

Salvage cutting is defined as the removal of dead trees, or trees damaged or dying because of injurious agents, to recover economic value (Helms, 1998). The emphasis in traditional salvage is generally on the removals, not on the stand structure retained. The salvage rubric often suffers from a 'one box fits all' approach to what should be highly variable silvicultural prescriptions. More importantly, there needs to be clear distinction between the disturbance and its effects, the salvage and its effects, and the desired stand structure. In some cases, the salvage operation can be like a second disturbance (D'Amato *et al*., 2011b). The objective of salvage treatments should be to design stand structures within the limits of the disturbance effects and existing structural features, *not* solely on timber removal. Timber removals in salvage treatments are often based on merchantability constraints and are guided by tree value rather than ecological objectives. Even after severe ice storms, there may be greater economic advantages to managing the residual stand than starting over (Goodnow *et al*., 2008).

Instead, salvage treatments should be opportunities to enhance resistance and resilience. Removals of dead or damaged trees should focus on future stand structure development and ability of that stand to achieve multiple objectives. Baker and Shelton (1998) demonstrated how rapidly poorly managed southern pine stands could be rehabilitated, providing an example of stand recovery with management. Additionally, salvage treatments may also attempt to anticipate mortality by removing injured or threatened trees. With strategic implementation, the result can be a more resistant and resilient stand structure.

Variable treatment intervals

Although disturbance regimes are often described with average return intervals or frequencies, these only approximate known disturbance patterns. As averages, they do not describe ranges and do not represent potential effects of global climate change or other changes (e.g. Baker and Ehle, 2001). Management regimes that attempt to emulate these disturbances or their effects should also not be constrained to consistent treatment intervals. These treatment intervals are described as thinning intervals for thinning treatments and cutting cycles for multi-aged stand treatments that regenerate a new age class. Classical silviculture describes both types of intervals as consistent in length because consistency represents an ideal: if appropriate intervals or cycles are known, then, conceptually, management is most efficient if they are achieved. However, consistent intervals are rarely achieved in practice because of a variety of operational issues such as weather, resource requirements and timber volume objectives.

For multi-aged silvicultural systems that attempt to emulate disturbance regimes, cutting cycles need not be consistent in length. Instead, they can be as variable as the disturbance regimes they emulate. The justification for a harvest entry can be to produce timber volume, reduce fuel hazards, salvage timber, create wildlife habitat or simply to emulate the effects of a disturbance on stand structures. Likewise, the magnitude of volume removals can be variable to achieve different objectives. Cutting cycle length and volume removals are related, with longer cycles compensated by heavier volume removals (O'Hara and Valappil, 1999). However, these patterns of correlated cutting cycle lengths and volume removals only offer descriptions of effects, not necessarily guidance for unregulated forests.

Operational challenges

Operational constraints may hinder multi-aged systems if management costs for tending or harvesting these stands are excessive. The smaller numbers of large logs from multi-aged forests may be uneconomical to harvest or transport. Processing capabilities for large logs, which are often produced from multi-aged forests, are also declining in some regions, resulting in discounts rather than premiums for large logs. There are also issues related to transferring land ownership of private lands in an era in which relatively short-term trust ownership is increasingly common. Long-term commitment to multi-aged strategies may be difficult with short-term planning horizons on these types of ownerships (Guldin, 2011).

Conclusions

In a world with increasingly variable disturbances and rapidly changing disturbance regimes, multi-aged management systems represent a promising approach for increasing resistance and resilience and limiting major disruptions to timber production and other ecosystem services. Whereas risk and uncertainty related to disturbances have always been a part of stand management, we see them becoming more complex in the future as disturbances become increasingly unpredictable. Disturbance regimes should be expected to change, in some cases profoundly, as a result of shifting climates, ongoing introductions of non-native organisms and numerous additional anthropogenic factors (e.g. landscape fragmentation, altered wildlife densities, legacies of past disturbance suppression).

Multi-aged stands are formed by multiple partial disturbances, natural and/or artificial, that regenerate new age classes or cohorts. Whether they arise from natural or anthropogenic processes, stands with a diversity of age classes and structures are generally more resistant and resilient to future disturbances. Thus, disturbance emulation through multi-aged management enhances the capacity of stands to endure future disturbances without severe effects and to integrate the resulting structures into existing landscape patterns.

This 'disturbance integration' strategy is highly appropriate for many public lands (e.g. multiple benefit lands) where management is often neither driven by timber production objectives nor regulated using traditional forest management concepts. Instead, landscapes may be highly variable and designed in anticipation of unpredictable future disturbance effects, climates and conditions. Management regimes that integrate variable length treatment intervals and variable production of ecosystem services can accommodate the uncertainty associated with disturbance. Further, salvage treatments can be designed to focus on residual stand structures rather than removing merchantable material. The movement away from traditional forest management concepts is, in effect, a form of deregulation that decouples management from production targets of some or all ecosystem services. This is a major change as it advocates a move away from the regulated mindset that has dominated forestry.

We believe a strong case exists for why multi-aged stands should generally be better able to absorb disturbances, especially when such disturbances depart from historical disturbance regimes. However, it must be acknowledged that there are surprisingly few studies that compare resistance or resilience between multi-aged and even-aged stands. Thus, our call for increased implementation of multi-aged management systems is actually rooted in two complementary goals: (1) increasing resistance and resilience of managed forests, and (2) expanding opportunities for rigorous comparison of disturbance effects between multi-aged and even-aged stands.

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Conflict of interest statement

None declared.

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