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CONCEPT PAPER

Building on the last "new" thing: exploring the compatibility of ecological and adaptation silviculture[1]

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Abstract: Sustaining the structure, function, and services provided by forest ecosystems in the face of changing climate and disturbance regimes represents a grand challenge for forest managers and policy makers. To address this challenge, a range of adaptation approaches have been proposed centered on conferring ecosystem resilience and adaptive capacity; however, considerable uncertainty exists regarding how to translate these broad and often theoretical adaptation frameworks to on-the-ground practice. Complicating this issue has been movement away, in some cases, from other recent advances in forest management, namely ecological silviculture strategies that often focus on restoration. In this paper, we highlight the areas of compatibility and conflict between these two frameworks by reviewing the four principles of ecological silviculture (continuity, complexity and diversity, timing, and context) from the perspective of global change adaptation. We conclude that given many commonalities between the outcomes of ecological silviculture and conditions conferring adaptive capacity, the four principles remain a relevant starting point for guiding operationalization of often theoretical adaptation strategies.

Key words: variable retention, biological legacies, variable density thinning, ecosystem complexity, emulation of natural disturbance regimes.

Résumé : Face aux changements climatiques et aux régimes de perturbations, le maintien de la structure, des fonctions et des services fournis par les écosystèmes forestiers représente un défi majeur pour les aménagistes forestiers et les responsables politiques. Plusieurs approches adaptatives ont été proposées pour relever ce défi, mais elles sont toutes axées sur le renforcement de la résilience et de la capacité d'adaptation des écosystèmes. Cependant, il existe une incertitude considérable quant à la manière de mettre en pratique ces larges cadres d'adaptation qui sont souvent théoriques. Pour compliquer ce problème, on s'est parfois éloigné d'avancées récentes en matière d'aménagement forestier, comme les stratégies de sylviculture écologique qui se concentrent souvent sur la restauration. Dans cet article, nous mettons en évidence les zones de compatibilité et de conflit entre ces deux cadres d'adaptation en passant en revue les quatre principes de la sylviculture écologique (continuité, complexité et diversité, moment d'intervention, et contexte) dans une optique d'adaptation aux changements globaux. Nous concluons qu'étant donné les nombreux points communs entre les résultats de la sylviculture écologique et les conditions qui confèrent une capacité d'adaptation, les quatre principes demeurent un point de départ pertinent pour guider la mise en œuvre de stratégies d'adaptation qui sont souvent théoriques. [Traduit par la Rédaction]

Mots-clés : rétention variable, legs biologiques, éclaircie à densité variable, complexité de l'écosystème, émulation des régimes de perturbations naturelles.

Introduction

Recent and anticipated changes in climate and disturbance regimes have magnified the challenges facing the long-term sustainability of forest habitats and ecosystem services (McDowell et al. 2020). The novelty and uncertainty of these changes, including an increasing frequency of extreme droughts and precipitation events and the proliferation of nonnative insects and diseases, have resulted in greater focus on recalibrating and, in some cases, abandoning the silvicultural strategies used historically to manage forests, primarily for timber resources, in many regions globally (Messier et al. 2015). Associated with this shift has been an increased emphasis on the development of adaptation strategies that create compositional and structural conditions that may be less vulnerable and (or) more able to adaptively respond to future changes in climate and disturbance regimes (Nagel et al. 2017). The movement towards silviculture for adaptation is certainly justified by observed and projected shifts in forest conditions; however, questions remain regarding what compatibility, if any, these strategies might have with current management approaches designed to restore and sustain ecological characteristics of natural forest ecosystems.

Prior to the more recent advent of adaptation silviculture, a major shift in management paradigms occurred in the late 20th century, as greater awareness of ecosystem ecology, natural forest dynamics, and conservation of biodiversity led to development of ecological silviculture as an alternative to strategies focused primarily on commodity production (Franklin et al. 1986;

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Hunter 1999). Although components of ecological silviculture were described and espoused by foresters and scientists as early as the late 19th and early 20th centuries (D'Amato et al. 2017), the more recent emphasis included widespread formalization of silvicultural systems that drew heavily upon natural forest development models to inform severity and frequency of regeneration harvests and associated levels of biological legacy retention (Franklin et al. 2007; Long 2009; Seymour and Hunter 1999).

Central to these methods is the emulation of the historical range of variability in natural disturbance patterns, with outcomes often targeted towards restoring and maintaining structural and compositional conditions documented for natural forest systems in a given region (Bauhus et al. 2009; Beller et al. 2020; Fassnacht et al. 2015; Fries et al. 1997; Stockdale et al. 2016). The reliance of these approaches on historical analogs and benchmarks has led to criticism regarding their utility in addressing forest management objectives in an era of global change, with associated novelty and uncertainty in forest conditions (Seastedt et al. 2008). Nonetheless, the general outcomes of ecological silvicultural strategies, including high levels of heterogeneity in structural and compositional conditions at stand and landscape scales, align with many recommendations for increasing forest adaptive capacity (D'Amato et al. 2011; Puettmann 2011), suggesting that there may be more compatibility between ecological and adaptation approaches than a cursory examination might suggest.

The goal of this paper is to examine the guiding principles of ecological silviculture in the context of emerging objectives associated with forest adaptation to global change. Specifically, we (*i*) outline the foundational principles of ecological silviculture in relation to original motivating objectives and contemporary adaptation strategies and (*ii*) illustrate the utility of silviculture based on natural developmental models in designing forest adaptation strategies. Our intent is to contribute to a path forward for adaptation silviculture that scaffolds on ecological silviculture principles to maximize integration, where appropriate, between these management regimes and frameworks. Through this integration, our ultimate goal is to increase levels of adaptation practiced by forest managers by demonstrating the utility of existing, on-the-ground practices and principles to address global change impacts.

Principles of ecological silviculture

The outcomes of ecological silviculture in the context of a wide range of taxa and objectives have been covered extensively in articles in the *Canadian Journal of Forest Research* and elsewhere over the past several decades (e.g., Carter et al. 2017; Franklin et al. 2019; Kuuluvainen and Grenfell 2012; Lõhmus and Kull 2011; Sullivan et al. 2017). Nevertheless, guiding principles for its application in silvicultural prescriptions have only recently been formalized (Palik et al. 2020), building on elements first introduced in the 1990s (Franklin et al. 1997; Seymour and Hunter 1999). The four foundational principles now recognized in the application of ecological silviculture are (*i*) continuity, (*ii*) complexity and diversity, (*iii*) timing, and (*iv*) context (Palik et al. 2020). Although the general intent of each principle historically has centered on restoration and sustainability of habitat, biodiversity, and natural processes, their relevance to silviculture for adaptation is summarized in the following sections.

(*i*) Continuity

The principle of continuity emphasizes deliberate management actions that provide for continuity in forest structure, function, and biota between pre- and postharvest ecosystems during regeneration harvests (Palik et al. 2020). Although intended to ensure continuity through retention and protection of a broad suite of biological legacies (sensu Franklin et al. 2000), including deadwood and advance regeneration, this principle has largely manifested in the selective retention of mature canopy trees as scattered individuals or groups during regeneration harvests, so called variable retention harvest (Franklin et al. 2019; Gustafsson et al. 2012; Urgenson et al. 2013). As such, retention harvests have often become synonymous with the practice of ecological silviculture, even though the full suite of principles associated with this management paradigm (as described in the following sections) is not being followed (Palik and D'Amato 2017).

Managing for continuity was originally conceived as a strategy to lifeboat species and processes from the preharvest community into regenerating areas in ways that emulated the outcomes of natural disturbance (Franklin et al. 1997); however, many objectives associated with adaptation are also achieved through these practices (Table 1). This congruity between ecological and adaptation approaches largely stems from the recognized importance of disturbance legacies, like surviving individuals or physical structures, in affecting patterns of response following disturbances and hence overall levels of ecosystem resilience (Johnstone et al. 2016). Recent discussions of adaptation strategies and associated resilience mechanisms now often refer to biological legacies as components of ecological memory (Puettmann et al. 2009); however, in practice, ecological silvicultural strategies such as variable retention harvesting systems remain the practical management tool to confer these mechanisms (e.g., J.A.C. Bergeron et al. 2017). Given the importance of legacies in affecting ecosystem reassembly and resilience, we expect managing for continuity to remain a critical element of forest adaptation strategies, regardless of the novelty of the ecosystem.

(*ii*) Complexity and diversity

The principle of complexity and diversity emphasizes the application of silvicultural treatments to create and maintain heterogeneity in structural and compositional conditions across multiple spatial scales (Palik et al. 2020). This principle was conceived in recognition of the variety of niches provided by forest ecosystems exhibiting a diversity of structures and canopy tree species, particularly evident in old-growth forests (Carey et al. 1999; Spies and Franklin 1996). Silvicultural systems developed to reflect this principle generally represent modifications of existing multi-age regeneration methods, such as selection and irregular shelterwood methods, to emulate aspects of prevailing natural disturbance regimes, including structural outcomes (Bauhus et al. 2009) and disturbance severities and frequencies (Seymour 2005). For regions dominated by relatively homogeneous forest conditions (e.g., plantations and second-growth ecosystems), variable density thinning, which combines thinning and regeneration methods to introduce spatial complexity in structure and composition (Carey 2003), has been a widely popularized approach reflecting this principle (Dodson et al. 2012; Donoso et al. 2020; Pukkala et al. 2011).

Of the principles associated with ecological silviculture, the principle of complexity and diversity has the greatest congruity with silvicultural strategies for adaptation to global change (Table 1). Beyond the previously mentioned linkages between biological legacies and ecosystem resilience, the recognized differential susceptibility of different species and tree size classes to disturbances and environmental stressors has resulted in adaptation strategies for developing mixed-species forests with complex structures (D'Amato et al. 2011; Puettmann 2011). A key difference between ecological and adaption silviculture in application of this principle resides in the long-term management outcomes associated with complexity; adaptation strategies focus more on sustaining ecosystem services and functions, whereas ecological silviculture strategies focus more on habitat and native biodiversity associated with "natural" ecosystems (Millar et al. 2007).

In practice, many of the ecological silviculture approaches developed to address the principle of complexity and diversity have direct translation to adaptation. For example, the heterogeneity in

Table 1. Example outcomes of application of four principles of ecological silviculture to biodiversity conservation and adaptation to global change.

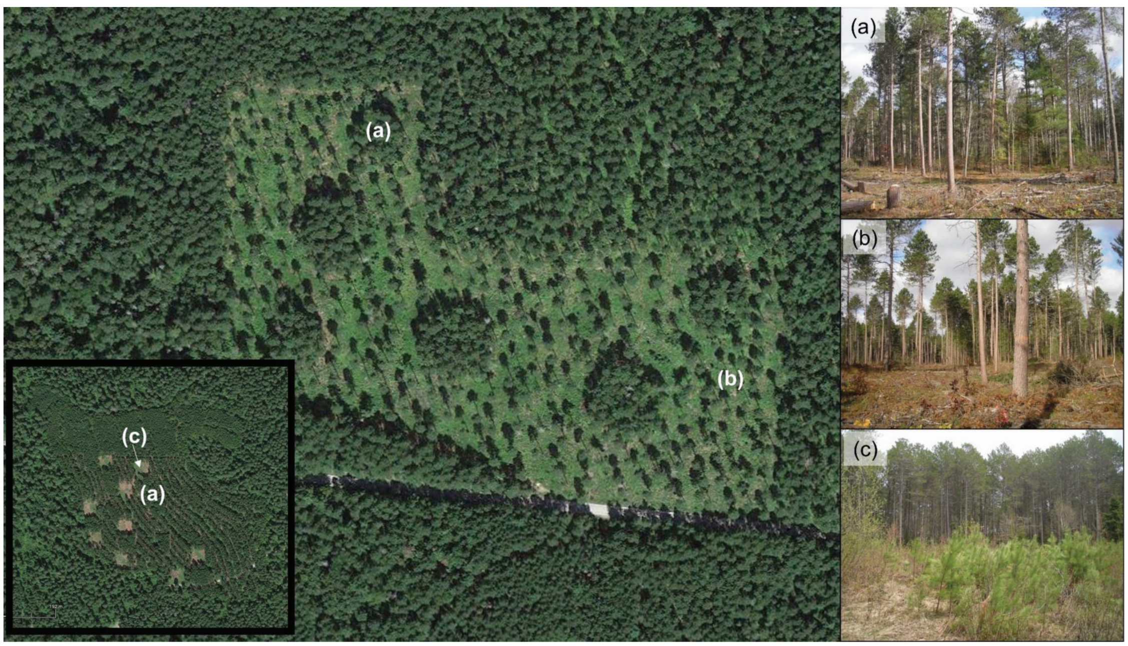
Original intent (e.g., biodiversity conservation)	Global change adaptation	Ecological silviculture practice
Continuity		
• Lifeboating of species requiring mature forest conditions (Franklin et al. 1997) • Greater diversity of food or energy sources from canopy species (Fedrowitz et al. 2014) • Large snags or deadwood for saproxylic and cavity nesting species (Lindenmayer et al. 2012)	• Maintain options for regeneration in face of uncertainty (Swanston et al. 2016) • Amelioration of harsh environmental conditions (Park et al. 2014) ○ Regeneration safe sites (shaded understory, decomposed wood) • Conservation of genetic diversity (Buchert et al. 1997) • Maintain ecological memory (Johnstone et al. 2016)	• Variable retention harvest systems (Gustafsson et al. 2012) that retain ○ scattered individuals and groups of mature trees ○ diversity of canopy species and forms ○ large dead trees • Protection of advance regeneration during harvests (Bergeron and Harvey 1997) • Protection of deadwood legacies through strategic deployment of leave-tree islands or aggregates (Rudolphi et al. 2014) • Deliberate retention and protection of disturbance-generated structures (e.g., charred and windthrown trees) during salvage logging (Thorn et al. 2020)
Complexity and diversity		
• Diversity of habitat and functional niches (Carey 2003) ○ Tree size classes ○ Deadwood decay classes ○ Live-tree spatial conditions (heterogeneity) ○ Tree, shrub, understory species	• Reduced vulnerability to disturbance (Churchill et al. 2013) ○ Spatial variability in fuels ○ Heterogeneity in wind risk (diverse heights) ○ Heterogeneity in potential host species (insects, disease) ○ Heterogeneity of tree sizes (host preferences, stress tolerance) • Multiple recovery and developmental pathways (Boisvert-Marsh et al. 2020) ○ Diversity of seed sources ○ Advance regeneration • Increased functional redundancy to offset impacts of species loss (Messier et al. 2019) • High levels of on-site mitigation potential (carbon storage) relative to intensive silviculture practices (Ford and Keeton 2017)	• Variable density thinning to create and maintain stand-scale mosaic of differing levels of canopy cover and resource availability (Roberts and Harrington 2008) • "Morticulture" (sensu Harmon 2001) to actively recruit large deadwood over time • Inclusion of large canopy gaps with legacy retention in selection and irregular shelterwood systems to balance structural retention with resource requirements of less-tolerant canopy species (Raymond et al. 2009)
Timing		
• Opportunity for multiple life cycles for species with slower development (Bartels et al. 2018) • Habitats for large tree specialists (live and dead trees) (Roberge et al. 2018)	• Long-term maintenance of options for adaptation from current overstory species (Depardieu et al. 2020) • Long-term amelioration of extremes in understory conditions (Martínez Pastur et al. 2019) • Reduced likelihood for compounding influence of harvesting with other stressors or disturbance (Paine et al. 1998) • Accumulation of large on-site carbon stores (D'Amato et al. 2011)	• Use of extended rotation periods that extend well beyond maximum mean annual increment (Curtis 1997) • Increase canopy residence time of long-lived species through extended cutting cycles and permanent legacy retention in stands managed with selection-based methods (Shields et al. 2008)
Context		
• Connectivity across landscapes and habitat gradients (e.g., riparian to upland, travel corridors) (Montigny and MacLean 2006) • Refugia at multiple scales (Hunter 2005) • Diversity of structures and composition at landscape scale (Kuuluvainen and Grenfell 2012)	• Reduced risk from landscape-scale stressors (drought) and disturbance (insects, fire, wind) (Seidl et al. 2018) • Greater options for adaptation potential at broad scales (Park et al. 2014) • Greater range of regeneration conditions for new species due to localized and landscape-scale heterogeneity in structure (Messier et al. 2015)	• Strategic zonation of silvicultural intensities across large ownerships and regions, using for example the TRIAD model (Seymour and Hunter 1992), to include ○ unmanaged ecological reserves representing a range of biophysical settings ○ intensively managed areas proximate to mills and other market opportunities

Table 1 (*concluded*).

Original intent (e.g., biodiversity conservation)	Global change adaptation	Ecological silviculture practice
	• Creation of functional networks through strategic maintenance and introduction of future-adapted species across landscape (Messier et al. 2019)	○ extensively managed areas applying the abovementioned ecological silviculture principles to emulate aspects of landscape and regional patterns of natural disturbance

Note: Examples of silviculture practices used to address each ecological silviculture principle are included. Adapted from Palik et al. (2020).

Fig. 1. Aerial view of variable retention harvest and variable density thinning (inset in lower left corner) with associated (*a*) unharvested reserve patches, (*b*) dispersed mature legacy trees, and (*c*) canopy openings. Although originally conceived to increase the complexity of species niches in homogenous managed forest ecosystems, such as the second-growth *Pinus resinosa* Aiton forests pictured, these strategies also generate features conferring ecosystem resilience, including (*a*) within-stand refugia, (*b*) areas of reduced fire and drought risk, and (*c*) areas for community reassembly via natural and artificial regeneration. Adapted from Palik et al. (2020). [Color online.]



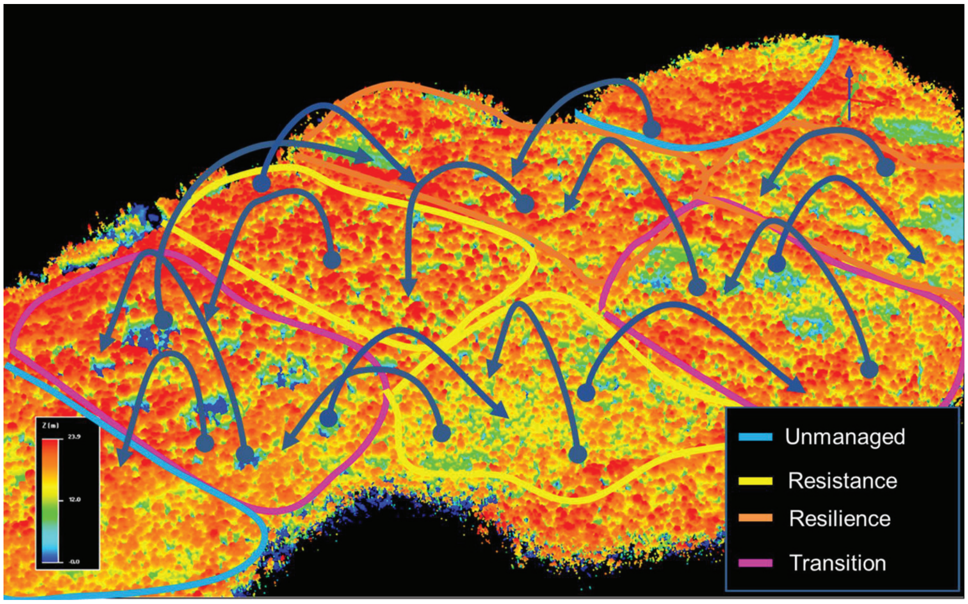
structural and compositional conditions created by variable density thinning and retention systems provide a range of stand-level adaptation pathways and functional conditions consistent with adaptation goals (e.g., Churchill et al. 2013; Fig. 1). These often include (*i*) unharvested reserve patches to serve as potential refugia for species of concern; (*ii*) canopy openings to provide opportunities for reorganization and functional enrichment via natural and artificial regeneration processes; and (*iii*) low-density, thinned areas that allow for tree-level selection of resilient forms and species (cf. Nolet et al. 2014) and within-stand patches of reduced vulnerability to crown fire and drought stress (Bottero et al. 2017). Given the recognized importance of complex, multiscale interactions across conditions such as these in conferring adaptation and resilience mechanisms (Messier et al. 2013), adaptation strategies building from these ecological silviculture approaches will remain relevant into the future.

(iii) Timing

The principle of timing recognizes the importance of basing silvicultural interventions, especially harvesting, on ecologically relevant time intervals, as opposed to traditional metrics associated with maximizing net present value or biological production of commercial species and products (Palik et al. 2020). In general, this principle reflects the long recovery and developmental periods needed to develop structural features associated with later stand developmental stages, such as large living and dead trees and multiple canopy layers (Gerzon et al. 2011), as well as the natural variation in return intervals for disturbances in a given region (Seymour and Hunter 1999). The management of forests using extended rotations is one approach used to incorporate the principle of timing into practice; this has proven effective at restoring late-seral structure and composition even when it incorporates periodic thinning (Bailey and Tappeiner 1998; Curtis 1995; D'Amato et al. 2010), while also sustaining high levels of wood production and carbon benefits (Mathieu et al. 2012). Moreover, varying rotation ages and cutting cycles across landscapes and within stands to reflect historical, natural variation in disturbance return intervals has been suggested as a strategy to sustain old forest habitat conditions in managed landscapes (Harvey et al. 2002; Kern et al. 2017), including in the context of future increases in disturbance frequency (Y. Bergeron et al. 2017).

However, this principle's focus on extended rotations and longer harvest intervals is contrary to the recommendation, for adaptation, to shorten these periods so as to rapidly adapt species

Fig. 2. Light detection and ranging (LiDAR) canopy height model of a portion of the New England Adaptive Silviculture for Climate Change installation at the Dartmouth College Second College Grant, New Hampshire, USA (Nagel et al. 2017). Polygons delineate 10 ha management units in which adaptation approaches for ecosystem resistance, resilience, and transition to climate change and disturbance impacts have been implemented. Arrows illustrate examples of potential multiscale functional linkages and feedbacks between different landscape elements (cf. Messier et al. 2019), including harvest gaps planted with species representing a range of functional traits, reserve patches, and fine-scale mosaics of canopy disturbance generated by hybrid single-tree and group selection approaches. LiDAR image provided by E. Broadbent, University of Florida, GatorEye Unmanned Flying Laboratory 2020 (http://www.speclab.org/gatoreye.html). [Color online.]



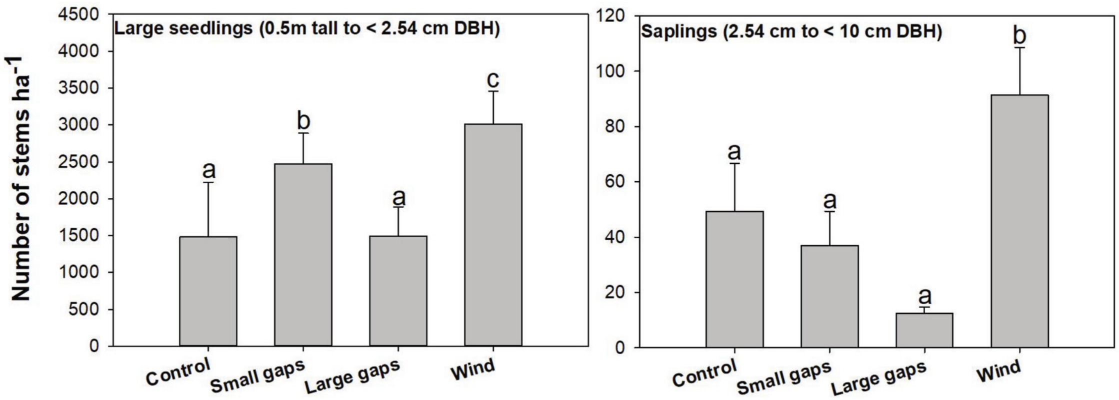
composition or management objectives to climate or disturbance impacts (Brang et al. 2014; Puettmann 2011), particularly for highly vulnerable forest types or stand conditions. In reality, climate and disturbance impacts are expected to display high spatial variability within a given region (Meddens et al. 2018; Stralberg et al. 2020), including nonuniformity in host loss to invasive species (e.g., Robinett and McCullough 2019) and within-species variation in climate sensitivity depending on underlying site conditions and landscape position (Case and Peterson 2005; Johnstone et al. 2010). As such, the appropriateness of the principle of timing in the context of adaptation may require refinement in its application, for example, restricting its use to lower vulnerability sites, so called climate refugia. These areas will be critical for sustaining mature forest conditions for sensitive taxa and may provide key functional feedbacks (sensu Messier et al. 2019) with younger portions of the landscape over time. Depending on species composition and management objectives, older forest areas could be maintained through uneven-aged methods based on shorter harvest intervals (e.g., Nolet et al. 2014) that emulate aspects of historical disturbance regimes (Seymour and Hunter 1999), while allowing flexibility to adapt ecosystem components to emerging novel dynamics. In addition, permanent retention of legacy trees (i.e., allowing some trees to live out their full life cycle; see principle of continuity) in areas otherwise managed on shorter rotations can allow for accumulation of genetic variation and adaptive capacity in a species and population by providing greater opportunity (i.e., time) for somatic mutations to occur (Hanlon et al. 2019).

(*iv*) Context

The last foundational principle, context, acknowledges the importance of accounting for the influence of silvicultural treatments in affecting landscape structure and function over time, particularly as it relates to provisioning for diverse habitat conditions and flows of matter and organisms at multiple spatial scales (Palik et al. 2020). This principle builds on the body of knowledge accumulated over the past several decades that demonstrates the spatially variable impacts of natural disturbances and the resultant diversity in landscape-level habitat conditions they maintain (Bergeron et al. 1999; Franklin and Forman 1987; Hunter 1993). Recommendations for implementing the context principle often involve spatially heterogeneous applications of the first three principles to generate a diversity of forest developmental stages with complex compositional and structural conditions across a landscape (Harvey et al. 2002; Kuuluvainen and Gauthier 2018). Of the four principles, context has proven most challenging to implement for several reasons, including constraints of ownership size and cross-ownership coordination; insufficient information on historical, landscape-level disturbance patterns; and lack of acceptance of potential reductions in timber revenues associated with extensive applications of ecological silviculture (Kuuluvainen and Grenfell 2012; Long 2009; J.R. Thompson et al. 2009).

Relative to managing for adaptation, a criticism of the context principle has been the reliance on historical natural disturbance regimes for guiding landscape-level implementation of silvicultural activities, particularly given observed and projected shifts in disturbance regimes under climate change (Beller et al. 2020; Klenk et al. 2009). Nevertheless, aspects of this principle related to acknowledging cross-scale interactions and maintenance of diverse and complex habitat elements are consistent with landscape-scale recommendations for adaptation based on complexity theory (Table 1; Messier et al. 2019). The latter places an emphasis on spatially strategic application of adaption strategies (e.g., enhancing functional diversity through regeneration activities) to enhance functional linkages across landscape units (Fig. 2; Messier et al. 2019), whereas such interventions have largely been guided by biodiversity objectives in the context of ecological

Fig. 3. Mean density of natural regeneration of species (all species pooled) projected to be "future climate adapted" under a high-emissions scenario (based on Iverson et al. 2019) in a large-scale ecological silviculture study in northern hardwood forest ecosystems in Wisconsin, USA (see Fassnacht et al. 2015 for study details). Treatments correspond to an unharvested control, selection treatments emulating single-tree fall gaps ("small gaps" = 90 m^2 gaps) and multiple-tree fall gaps ("large gaps" = 260–470 m^2 gaps), and irregular shelterwood systems emulating mesoscale wind disturbance ("wind"). Bars are means and standard errors (n = 3), and values with different letters are significantly different at $p < 0.05$ based on analysis of covariance (ANCOVA) and Tukey's honestly significant difference (HSD). DBH, diameter at breast height (breast height = 1.30 m).



silviculture. Despite these differences in framing, operational implementation of landscape-level adaptation strategies will likely consider ecological context and include landscape variation in the inclusion of ecological silvicultural principles, such as continuity, complexity and diversity, and timing (Kuuluvainen and Gauthier 2018; Ontl et al. 2020), but with a pronounced emphasis on their resultant functional response to climate and disturbance (Aubin et al. 2016).

Natural development models and adaptation to novel stressors

The framing of the previously mentioned principles of ecological silviculture around emulation of natural forest dynamics and resultant structural and compositional conditions of natural forest ecosystems has led some to question their relevance in addressing the novel stressors and dynamics facing many forests globally (e.g., Messier et al. 2015). Instead, a point of emphasis for many adaptation strategies has centered on deliberate shifts in composition, including increasing the representation of species projected as adapted to future climate and disturbance regimes (Aubin et al. 2016; Iverson et al. 2019; Muller et al. 2019), or encouraging regeneration and increased abundance of nonhost species for a given introduced pest or pathogen (D'Amato et al. 2018). It can be argued that these tactics have little historical analog, and thus the principles of ecological silviculture have little relevance, yet an understanding of the regeneration and disturbance processes that lead to recruitment of functionally similar native species (e.g., shade tolerance or reproductive strategy) remains a useful construct for guiding adaptation and ecosystem transition.

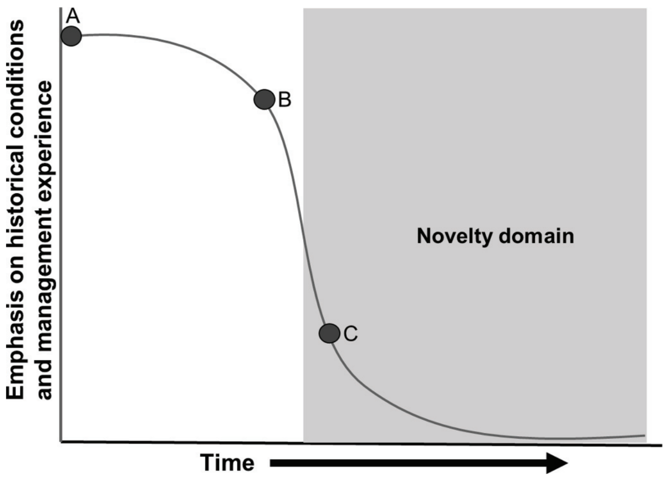
As an example, recent projections of future tree distributions indicate high potential for "new species" to expand in regions dominated by northern hardwood ecosystems in northeastern North America (Iverson et al. 2019). Given the general negative correlation between shade and drought tolerance (Niinemets and Valladares 2006), the majority of these "future-adapted" species will be intolerant to mid-tolerant of shade. Traditionally, these species would likely be encouraged using even-aged regeneration systems, such as clear-cutting with planting, to increase their representation for adaptation (Pedlar et al. 2012). But such recommendations run counter to the prevailing silvicultural systems used for the northern hardwood ecosystem in the region (uneven-aged methods), which increasingly incorporate continuity, complexity and diversity, and timing, and ignore the strong dominance of shade-tolerant canopy tree species currently and historically characterizing these forests (Russell et al. 2014; Thompson et al. 2013). Instead, multi-age silvicultural approaches based on elements of natural disturbance may still be appropriate, such as continuous cover-irregular shelterwoods that emulate the mesoscale wind events that historically provided recruitment opportunities for species of lesser shade tolerance (Fig. 3; Hanson and Lorimer 2007). Such an approach would provide adaptation strategies that build from, versus run counter to, current operational and ecological contexts.

For example, regeneration responses to natural-disturbance-based regeneration methods in Wisconsin, USA, included a greater abundance of future-climate-adapted species (based on Iverson et al. 2019) in irregular shelterwood treatments that emulated structural and resource conditions observed following microbursts and other mesoscale events (Fig. 3; Hanson and Lorimer 2007). In contrast, selection-based treatments emulating frequent gap-scale events primarily recruited climate-vulnerable, shade-tolerant species (Fig. 3; Reuling et al. 2019). Although these latter treatments are appropriate as resistance strategies for climate change refugia, silvicultural systems that emulate mesoscale events are most likely more suitable for managers seeking to increase representation of future-adapted species and functional responses as part of resilience and transition adaptation strategies (cf. Nagel et al. 2017). In this case, seeking congruity between recommended adaptation strategies and prevailing management frameworks, such as ecological silviculture, may actually lead to increased implementation of adaptation, compared with more generic or theoretical adaptation recommendations, which can appear abstract in the contexts of local management experience and forest conditions (Timberlake and Schultz 2017).

Conclusion

Given the tremendous uncertainties around future changes in climate and disturbance regimes, it is naïve to assume that any single management framework or approach will be wholly successful at sustaining ecosystem services and functions into the future. Similarly, there is danger in rapid dismissal of contemporary management frameworks, such as ecological silviculture, that, despite originating under differing historical motivations,

Fig. 4. Conceptual representation of the utility of natural developmental models, and derived principles of ecological silviculture, and management experience in informing silviculture as global change progresses. Points approximate (A) the period of popularization of ecological silviculture approaches; (B) current conditions in which novel dynamics have begun emerging, yet historical knowledge and experience remain relevant; and (C) the future — a no-analog period in which novelty predominates. Aspects of the principles of ecological silviculture, such as managing for continuity in structure and process and deliberately encouraging structural and compositional complexity at multiple spatial scales, remain relevant across the periods depicted; however, the utility of historical analogs for developing such prescriptions diminishes as change progresses.



may provide forest conditions that confer future adaptive capacity (Messier et al. 2015). The management community's ability to translate broad and often theoretical recommendations for adaption into tangible, localized silvicultural strategies will require clear operational linkages to current practices and should be easily related to experiences that are familiar (Ontl et al. 2018). This includes recognizing commonalities between operational outcomes of the ecological silviculture principles described herein and strategies being advanced to manage for complex adaptive systems and confer resilience in the face of global change (Messier et al. 2013).

In many respects, the early reluctance to widely adopt ecological silviculture practices, such as variable retention harvesting and variable density thinning, was due in part to a poor cross-walk of these practices to familiar silvicultural approaches such as irregular shelterwood methods (Palik et al. 2020). Once this cross-walk was made, adoption of, for example, variable retention harvesting began to be more widely accepted (Gustafsson et al. 2012). Building adaptation strategies from existing and compatible frameworks, such as ecological silviculture, may avoid similar pitfalls and confusion and allow for more rapid development of the operational adaptation strategies urgently needed to address global change.

The continued evolution of novel forest dynamics, and movement towards undesirable tipping points, will increasingly diminish the relevance of historical dynamics and conditions for informing silviculture (Fig. 4). However, as we have pointed out, the principles of ecological silviculture (Palik et al. 2020) will continue to serve as key guides for development of adaptation silviculture. The central premise of ecological silviculture focusing on the maintenance and creation of structural and functional complexity and heterogeneity, and compositional diversity at multiple scales, through an understanding of ecological dynamics, remains relevant to addressing the uncertainties of future global change (Messier et al. 2015). Monitoring the outcomes of ecological silviculture treatments in the face of changing conditions will remain critical for determining the degree to which an adaptation strategy departs from current practice and thus the need for more novel transition approaches. It is likely that progression over time towards more novel conditions (e.g., Fig. 4) and undesirable ecological thresholds will increase the reliance on more experimental transition strategies; however, core elements of the ecological silviculture principles described herein should remain central to these approaches, given their consistency with our understanding of the ecosystem properties conferring resilience (I. Thompson et al. 2009).

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