Journal of Forestry
https://doi.org/10.1007/s44392-025-00064-7

REVIEW

Ecological Silviculture in an Era of Climate Change

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Received: 28 April 2025 / Accepted: 15 October 2025

Abstract

Silviculture in North America has undergone several paradigm shifts over the last 100+ years. The most recent paradigm has been termed ecological silviculture, which is an approach for stand management based on understanding and emulation of natural disturbance and forest development, with the objective being to bring managed forests closer to a natural model in structure and composition to maintain a full suite of ecosystem services. Ecological silviculture is best thought of as an approach used in specific parts of a landscape characterized by a *TRIAD* of balanced forestry goals, including production forestry, conservation reserves, and multi-objective forestry, with the latter being the place where ecological silviculture is most applicable. We review the concept of ecological silviculture with a goal of showing why it is a unique part of the balanced forestry approach. Moreover, we consider ecological silviculture in the context of climate change, asking if we have shifted to an era where ecological silviculture has been superseded by adaptation silviculture? Our take home message is that given its underlying principles and consideration of diverse societal values and ecosystem dynamics, ecological silviculture can also be silviculture that adapts to changing but uncertain future ecological and social conditions.

Keywords Adaptation · Balanced forestry · TRIAD · Natural disturbance · Stand development

Study Implications This review provides a background on important forestry paradigm shifts over time that reflect changing societal goals. The most recent paradigm has been termed ecological forestry and is addressed with silviculture based on emulation of natural disturbance and stand development. In an era of climate change, we ask if a new paradigm of adaptation is needed. We show how ecological silviculture is also well suited to addressing adaptation goals.

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Published online: 02 December 2025

Introduction

There have been numerous synopses of the history of the forestry profession and the silvicultural field in North America; however, a rather poignant summary was presented in a plenary address at the 2004 Great Lakes Silviculture Summit (Palik and Levy 2004) by Robert (Bob) Seymour, then Curtis Hutchins Professor of Forest Resources at the University of Maine. Seymour reviewed the major eras of forestry, and the paradigm shifts that led to them (Seymour 2004). In order, these included the *custodial era*, which focused on wildfire suppression and securing regeneration after an *era of exploitive logging*. This was followed by the *selective cutting era*, a period where the forestry profession pursued selection cutting and partial harvesting, even when these were ill suited to the ecosystem (Kelty and D'Amato 2006). Next was the *multiple use/production era*, when forestry largely abandoned selection cutting and widely adopted even-aged silvicultural approaches (Fox et al. 2007; McEwan et al. 2020). The latter was seen by many foresters as a path to multiple use, even when it led to marginalization of ecosystem services beyond timber production (e.g., Stevens and Montgomery 2002).

Eventually, criticisms of the production approach ushered in the next era of forestry, which Seymour labeled *balanced forestry*. Balanced forestry is a landscape-scale consideration of management that may range from intensive production to conservation, often as part of a TRIAD consisting of plantations and reserves embedded in a matrix of ecological forestry (Seymour and Hunter 1992; Himes et al. 2022), or as a *shades of green landscape* with gradations in management intensity and objectives between these end points (Franklin et al. 2018). The deliberate inclusion of ecological forestry in this mix was the result of yet another paradigm shift; to a *New Forestry* (Franklin 1989; Seymour and Hunter 1992, 1999); one in which all ecosystem services are valued equally and are sustained through intentional management of forests as whole ecosystems.

Silvicultural and conservation approaches for achieving two-thirds of the TRIAD (production forestry and conservation reserves) were well-established at the time of its conception; however, ecological forestry, using approaches that balance the diversity of social, ecological, and economic goals and outcomes in the forest matrix, were very much in their infancy (Seymour and Hunter 1992, 1999). Different silvicultural approaches have been suggested for ecological forestry; however, early recommended guiding principles largely intersect with what we now call *ecological silviculture*, an approach grounded in understanding and emulating natural disturbance regimes and subsequent forest development, with an emphasis on restoring or sustaining structural and compositional complexity across all stages of forest development (Seymour and Hunter 1992; Messier et al. 2009; Côté et al. 2010; McGrath et al. 2021; Palik et al. 2021).

Stewards and stakeholders during the balanced forestry era have continued to grapple with achieving integrated social, economic, and ecological outcomes from managed forests, with a central emphasis on biodiversity conservation (Himes et al. 2022). This challenge remains today across much of the global forest. However, climate change and related novel stressors, like introduced insects and pathogens, further complicate these efforts, as they have generated an unprecedented number of challenges to sustaining forests using stewardship approaches based on natural models, which are often at the core of ecological silviculture. These challenges call into question the relevance of ecological strategies and silvicultural systems built on historical knowledge of natural ecosystem dynamics, that is, are we looking too much to the past with an ecological silvicultural approach?

At issue is whether we have already entered a new era of forestry, one driven by the need to adapt to changing climate and associated stressors, such that ecological silviculture is increasingly irrelevant. This question, while valid, is rhetorical for us, as our take home message is that ecological silviculture can also be silviculture that adapts to changing but uncertain future ecological and social conditions.

Ecological forestry in the context of climate change was the theme of a 12 part webinar series that ran from September 2023 through August 2024 and was sponsored by the US Fish and Wildlife Service-Forest Ecology Working Group and the Northern Institute of Applied Climate Science (www.climatehubs.usda.gov/hubs/northern-forests/topic/ecological-forestry-context-climate-change-webinar-series). This special issue of the *Journal of Forestry* includes several papers that are based on presentations from the series, including our own.

Here we synthesize our webinar content to review the basic concepts of ecological silviculture, including the concept of *disturbance archetypes* that serve as models for silviculture systems. We follow this by considering the basics of adaptation silviculture. We finish by showing how the two paradigms and associated approaches are compatible, highlighting four real-world examples of application.

Basics of Ecological Silviculture

At its core, ecological silviculture is an approach for stand management based on understanding and emulation of natural disturbance and forest development. With ecological silviculture, there is a greater integration of the patterns, processes, and structures expected under natural disturbance regimes and subsequent forest development and how these can be supported and emulated with silvicultural systems (Palik et al. 2021). The premise is to bring managed stands closer to a natural model in structure and composition to support a full suite of ecosystem services (Puettmann et al. 2012; Palik and D'Amato 2017).

This understanding of natural disturbance and development has been conceptualized into *disturbance archetypes*, which are model systems for major types of forest ecosystems that describe their disturbance regimes, developmental dynamics, and structural and compositional features (Table 1; Franklin et al. 2018; Palik et al. 2021). The archetypes vary in details of disturbance agent, spatial scale and pattern of disturbance, and resultant forest structure (Table 1). They also differ in the appropriate stand developmental model that serves as the basis for a silvicultural system. For instance, the infrequent, severe disturbance archetype is characterized by sequential development, beginning with a canopy (regeneration) disturbance and progressing through a preforest stage, which is a period when herbaceous and

Table 1 Characteristics of natural disturbance archetypes based on historical understanding and serving as basis for ecological silvicultural systems

Disturbance archetype	Agent	Disturbance scale	Developmental model	Preforest condition[b]	Age structure[c]	Example Ecosystems[d]
Infrequent severe	Fire, wind	Stand	Sequential[a]	Likely	Single cohort leading to multi-cohort	Douglas-fir-western hemlock; Aspen mixedwood
Frequent low severity	Fire	Stand	Continuous woodland mosaic	Preforest-like condition perpetuated	Two or more cohorts	Longleaf pine woodlands; Ponderosa pine-dry-mixed conifer
Gap to meso-scale	Wind, ice, insects, pathogens	Gap to patch	Gap mosaic to large-patch mosaic	Unlikely	Strongly multi-cohort	Northeastern northern hardwoods; Acadian mixedwood
Mixed severity	Fire, wind, insects, pathogens	Patch to stand	Sequential to large-patch mosaic	Varies with severity	Single, two-, multi-cohort	Great Lakes mixed pine; Southern pine oak

[a]Following a stand-scale disturbance a sequential model includes preforest, young, mature, and old forest stages over much of stand area

[b]A period after a canopy disturbance when herbaceous and shrub species dominate the site

[c]Typical in mature and old stages under the historical natural disturbance regime

[d]From Palik and D’Amato 2023

shrub plant communities dominate a site (Swanson et al. 2014), followed by young, mature, and old-forest stages. This model, while similar to other stand development models (e.g., Smith et al. 1997), places greater emphasis on whole ecosystem responses to disturbance, including legacies of the pre-disturbance forest (Franklin et al. 2002). The other archetypes share elements of this sequential model; for example, they are all characterized by a canopy disturbance that results in regeneration (Fig. 1). However, they differ in other ways, including the spatial and temporal scale of disturbance and the expression of development stages. For instance, frequent fire ecosystems are better described by a model based on a continuous woodland mosaic (Larson and Churchill 2023), whereas the gap-scale archetype and a mixed-severity archetype express the sequential development model, but often at smaller scales within stands (Table 1).

Box 1 Examples of ecological silvicultural systems for four archetypes with climate change considerations. Adapted from Palik and D'Amato (2023)

Infrequent severe disturbance archetype: Douglas-fir-western hemlock (DF-WH) forests

The DF-WH ecosystem was the model for developing the infrequent severe disturbance archetype and was the ecosystem where the sequential developmental model outlined above was first described (Franklin et al 2002). Distinctive elements of the ecological silvicultural system include deliberate management for a pre-forest stage (Swanson et al. 2014), as well as management for an extended young forest stage, during which regeneration may establish over decades (Tappeiner et al. 1997). It also includes use of variable retention harvesting during the mature and old forest stages as a tactic to address the principle of continuity of large living trees and deadwood (Franklin and Donato 2020)

Many of the ecological tactics outlined in this silvicultural system are also climate adaptive (Wheeler et al. 2023), including maintaining lower densities across development stages, with the expectation of enhanced vigor of individuals that are better able to resist dryer conditions and novel pest threats. Deliberate management for an old forest stage, as well as retention of old trees at harvest in the mature stage, increases the representation of trees that are important habitat elements and more resistant to wildfire and drought, both of which are expected to increase with climate change. At the same time, these legacy elements may become increasingly important for buffering microclimatic extremes during the pre-forest stage and providing regeneration safe sites (cf. Wolf et al. 2021; Zhang et al. 2023)

Frequent low severity archetype: Longleaf pine woodlands

Longleaf pine woodlands of the US southeastern coastal plain are the quintessential frequent fire ecosystem (Mitchell et al. 2006). The ecological silvicultural system for longleaf pine woodlands varies depending on broad objectives of either conversion from other species back to longleaf pine dominance or maintenance of intact longleaf stands (Jack et al. 2023). Still, all approaches are inherently grounded in use of frequent prescribed surface fires at all stages of development. Fires reduce abundance of hardwood species and maintain lower tree densities characteristic of woodlands and create seedbed conditions necessary for longleaf pine regeneration. Selection harvests of individual to small groups of canopy trees emulate small-scale mortality events from lightning and bark beetles, providing the resource environments needed for regeneration opportunities

Restoring and maintaining longleaf pine as the dominant species with an ecological approach is also an important climate adaptation tactic (Jack et al. 2023). For instance, longleaf pine is drought tolerant and more resistant to damage from severe winds, both of which are expected to increase in the longleaf pine region. The potential for increased proliferation of invasive plants with climate warming underscores the importance of restoring and supporting a frequent fire disturbance regime with prescribed fire, which serves to support a vigorous and diverse native ground layer plant community which is more resistant to invasion. In some cases, planting of future adapted ground layer and tree species, may be necessary to sustain suitable fuel conditions for sustaining frequent, low severity fire into the future (Holbrook and Puhlick 2025)

Gap-scale archetype: Temperate European beech forest

Fig. 1 Examples of disturbance and legacy creation stage (left column) and associated ecological silvicultural treatments (right column) for (**a**, **b**) infrequent, severe, (**c**, **d**) frequent low severity, (**e**, **f**) gap to meso-scale, and (**g**, **h**) mixed severity archetypes. a = Surviving patches of trees following wildfire in Douglas-fir-western hemlock forests, Willamette National Forest, OR, b = variable retention harvest in Douglas-fir-western hemlock forests, Olympia region, WA, c = ponderosa pine forest maintained by frequent prescribed fire, Coconino National Forest, AZ, d = hybrid single-tree/group selection with prescribed fire at Lubrecht Experimental Forest, MT, e = multiple-tree fall gap from windstorm in northern hardwood forests, Munising, MI, f = continuous cover irregular shelterwood in northern hardwood forests, Green Mountain National Forest, VT, g = canopy opening resulting from disease pocket and surface fire in red pine forest, Itasca State Park, MN, h = variable retention harvesting red pine forests, Chippewa National Forest, MN. All photos by A. D'Amato, except (a) J. Franklin ▶

Beech (*Fagus sylvatica*) dominated forests of eastern Europe are a good example of a disturbance regime characterized by frequent small canopy gap disturbances punctuated by less frequent disturbance of intermediate severity (Nagel et al. 2023). Developmental stages are manifested at the gap scale and less often at the large patch scale with intermediate disturbance. An ecological silvicultural system for this ecosystem mimics the gap to intermediate severity canopy disturbance regime using selection and irregular shelterwood methods, with an emphasis on tactics to transition abundant young and mature forest stages to an old forest stage, with complex age and size structures, diverse tree species assemblages, and substantial amounts of large deadwood

Increasing temperatures and the occurrence of hot droughts are concerns for central Europe and the European beech ecosystem, as both result in reduced growth and increasing mortality of the species. Tactics associated with an ecological approach, such as restoring and sustaining underrepresented trees species, including up to twelve native species, have a parallel adaptation benefit as some of these have greater heat and drought tolerance than beech (Nagel et al. 2023). Implementing frequent gap-scale harvesting in mature stage stands to establish new tree cohorts on a more frequent basis may also be climate adaptive if this helps to facilitate adaptation of the local gene pools for a species to a changing climate. Nevertheless, the pervasive impacts of deer herbivory may extend pre-forest conditions and selectively reduce certain canopy species creating the need for exclosures or other protection measures in the future (Nagel et al. 2015)

Mixed severity archetype: Southern pine-oak forests

The pine (*Pinus*) and oak (*Quercus*) forest of the southcentral eastern US is a good example of the mixed severity archetype (Hart et al. 2023). These ecosystems commonly have up to ten co-occurring species in stands with complex age and size structures resulting from interactions of wind and surface fire of varying scale and severity. An ecological silvicultural system for this ecosystem reflects the within stand structural heterogeneity that results from this disturbance regime, emphasizing patch scale regeneration harvests with reserve (legacy) trees, use of prescribed fire at various stages of development, and thinning overstocked fire sensitive hardwoods in favor of pines (Hart et al. 2023)

As in many regions, climate change expectations for the US pine-oak region include increasing temperatures and frequency and severity of droughts, conditions that also may result in more frequent and severe catastrophic fire. An important adaptation tactic is to restore or sustain the diverse tree species assemblage's characteristic of this ecosystem, as some species will be better adapted to climate changes (Hart et al. 2023). Additionally, density reduction of fire sensitive hardwoods should enhance vigor of oaks and pines by increasing available soil moisture under drought conditions

The archetypes, when applied to a given ecosystem, are used as the basis for developing silvicultural systems, including regeneration methods (Fig. 1), as well as the timing, frequency, and type of intermediate treatments applied over time. Elsewhere, we have documented examples of real-world application of ecological silviculture systems based on the archetype models (Palik and D'Amato 2023; Box 1). The differences in characteristics of specific ecosystems result in equally variable details of the silvicultural systems derived from them, even within the same archetype. Still, there are commonalities among these silvicultural systems, regardless of


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

the ecosystem and its archetype, in that they all address a core set of foundational principles.

The foundational principles of ecological silviculture have been presented in detail elsewhere (Franklin et al. 2018; Palik et al. 2021). Briefly they include: i) *continuity*, which is the provisioning of structure, biota, and function from a pre- to post-disturbance forest; ii) *complexity/diversity*, addressing the development of structural complexity and species diversity in established stands as they develop; and iii) appropriate *timing* of silvicultural interventions to allow adequate time for recovery and development of complex structure. A fourth principle, *context*, underscores the need to consider how stand-scale actions accumulate to affect landscape structure and function, including metrics such as patch distribution and connectivity (Franklin and Forman 1987).

How do the archetype models and foundational principles stand up to the challenges of climate change? Before we address this question, it is useful to review considerations for adaptation silviculture.

Adaptation Silviculture

Inherent to silviculture is the process of defining desired future conditions and planning the strategies that will modify stand development to achieve those conditions. In the past, our knowledge of how forests respond to disturbances and climatic conditions has often provided predictable outcomes and pathways of forest stand development, and this has continued to be the case with ecological silviculture, as reflected in the central role of disturbance archetypes in guiding ecological silvicultural systems. However, the accelerated rate of climate change occurring in many forested regions, along with the additional stressors that humans impose on ecosystems, and the uncertainty in the outcomes of interactions among disturbances, climate change, and tree establishment, growth, and survival has decreased our certainty in predictive outcomes (Puettmann 2011). In some cases, transformation of ecosystems results in the emergence of new species assemblages for which there are no natural analogs (Moore and Schindler 2022), as well as feedback loops that increasingly limit opportunities to sustain structures and plant communities historically associated with a given forest ecosystem (Brooks et al. 2004). Such dynamics challenge the relevance of past practices and desired conditions for silvicultural decision making in an increasingly novel environment.

Correspondingly, silvicultural strategies to achieve desired future conditions with climate change will require novel approaches, or modification of existing approaches, to adapt to changing conditions. This need to adapt past practice to present challenges is not new to forestry, as silvicultural systems have long been presented as a working hypothesis that should be refined as new information becomes available (Smith 1962). To this end, the temporal uncertainty in the changes in climate and disturbance regimes at a specific location will require flexibility and frequent adjustment in approaches to modify forest development to meet desired conditions (D'Amato et al. 2023a). This frequent adjustment and application of treatments to address climate vulnerabilities and impacts, to sustain the delivery of desired values and services, encapsulates adaptation silviculture.

The flexible and iterative nature of adaptation silviculture is critical given susceptibility to disturbances and climate extremes often differ throughout the life stages of a tree and developmental stages of a forest. With adaptation silviculture, a key emphasis of silvicultural treatments is responding to the vulnerabilities and challenges tied to a given developmental stage. For example, changing climate and disturbance dynamics during the disturbance and legacy creation and pre-forest stages may require site preparation activities and reforestation practices that once were unnecessary or optional to enhance regeneration, establishment, and survival (Fig. 2). This may include activities such as broadcast burning or whole-tree harvests to reduce surface fuels loads and allow new regeneration (natural or artificial) a better chance of survival if exposed to wildfire in locations expected to experience increased fire frequency. At the same time, increasing potential for short-interval fires (i.e., reburns) may limit regeneration success by reducing seed availability and increasing microsite extremes due to reductions in structural legacies in post-burn environments (Hoecker et al. 2020).

Adapting reforestation practices to the abovementioned conditions may require planting efforts during the pre-forest stage that focus on matching seedlings to "climate-buffered" microsites (e.g., adjacent to downed woody material or existing vegetation; Marshall et al. 2023), a process potentially aided by application of emerging digital forestry tools for mapping microclimate conditions (Marsh et al. 2022). Moreover, adaptation silviculture will likely include artificial regeneration of new genotypes and species better adapted to changing conditions, through use of assisted migration and planting of genotypes or species resistant to novel pest dynamics (Pedlar et al 2012; Clark et al. 2023; Fitts et al. 2025). Finally, across most regions, the increasing proliferation of invasive plant species, often linked to climate change (Bradley et al. 2010), may make vegetation management through site preparation and release treatments requisite strategies across forest developmental stages to ensure regeneration success given these novel dynamics (Fig. 2; Pile Knapp et al. 2023).

Given the complex and uncertain changes facing forests, a legitimate question is whether ecological silviculture is increasingly irrelevant, given its grounding in natural disturbance and stand development linked to environmental conditions that may

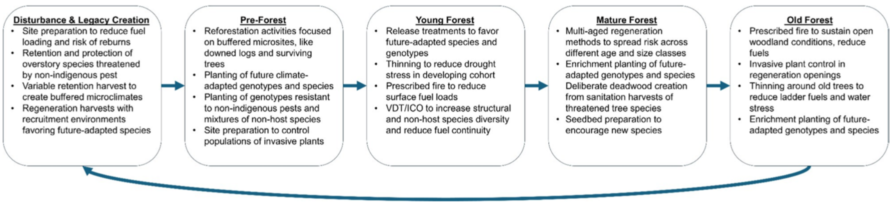

Fig. 2 Examples of adaptation silvicultural practices applied across a forest stand development model to guide ecological silvicultural systems. Arrows reflect a sequential development model associated with infrequent, severe disturbance archetype, with developmental sequence and silvicultural treatments often occurring at gap and patch scales in other disturbance archetypes. Note in young forest: VDT: variable density thinning; ICO: individuals, clumps, opening

no longer exist. In other words, have we entered a new era of adaptation forestry and silviculture? The answer harkens back to Seymour (2004), where he reminds us, that paradigm shifts in silviculture, while *at their times were embraced with enthusiasm….in retrospect, often seem to be excessive oscillations of the pendulum*. His message was a caution to learn from the past as we look to the future when charting a path for silviculture. With this caution in mind, we show how ecological silviculture is still relevant, even in an era of climate-adaptation.

Reconciling Ecological and Adaptation Silviculture

There is an increasing sense of urgency to implement silviculture that is climate adaptive (Messier et al. 2019; Nagel et al. 2017). At the same time, there is a recognition that for most of the global forest, outside of plantations, management needs to become purposefully ecosystem-focused if the full range of services that society demands from forests are to be sustained (Puettmann et al. 2012). Rightfully, stewards and stakeholders may ask if these two aims are mutually exclusive, that is, can silviculture be climate-adaptive and ecological or are we entering a new era where ecological silviculture based on past natural models is irrelevant.

We have addressed this issue in detail elsewhere (D'Amato and Palik 2021), where we cross-walked the foundational principles of ecological silviculture to climate adaptation goals and argue the two aims are directly mutually compatible. This compatibility stems from general congruity between the outcomes of ecological silviculture, including complex structural, compositional, and functional forest conditions at multiple spatial scales, and those associated with conferring ecosystem resilience and adaptability (Messier et al. 2019). In short, the inclusion of climate change considerations in ecological silvicultural systems as applied to the four major disturbance archetypes underscores the compatibility between ecological silviculture and climate adaptation (Palik and D'Amato 2023). We give an example of this interpretation for each disturbance archetype highlighted in Box 1.

The examples illustrate that the archetype models as a basis for silvicultural systems can remain broadly valid, such that knowledge of how forests looked and worked naturally prior to Euro-American settlement remain relevant (D'Amato and Palik 2021), albeit with some changes and challenges as novel conditions emerge (Table 2). For example, the importance of a preforest stage is not consistent among the archetypes under historical dynamics (Table 1) but may become increasingly likely with climate change as dryer conditions prevail and as multiple disturbances compound to delay regeneration (Table 2). This includes the gap-scale archetype, for which a pre-forest stage was historically rare or short in duration, but is now becoming increasingly common in some regions of the US due to herbivory, competition from non-indigenous and native plants, and shifts in disturbance regimes (Vickers et al. 2019; Miller et al. 2023).

Similarly, increases in the severity and frequency of disturbances, as well as the continued proliferation of non-indigenous insects and pathogens, may limit the development of the multi-aged stand structures with abundant old trees that are characteristic of most natural archetypes (Table 2). Climate-adaptive strategies, such

Table 2 Potential changes in disturbance archetypes with climate change as novel conditions emerge

Disturbance archetype	Agent	Disturbance scale	Developmental model	Preforest condition	Age structure[a]
Infrequent severe	Fire, wind, insects	Stand	Prolonged sequential	Likely	Single to two-cohort depending on reburn interval
Frequent low severity	Fire, insects, drought	Stand	Woodland mosaic with prolonged treeless patches	Likely shift from patch to stand-scale with increasing drought and compound disturbances	Single to two-cohort depending on severity and scale of compounding disturbance
Gap to meso-scale	Wind, ice, insects, fire, pathogens	Patch	Large-patch mosaic	Likely at patch-scale, particularly where invasive plants are abundant	Two to multi-cohort depending on non-host-abundance for insects and pathogens
Mixed severity	Fire, wind, insects, Drought, pathogens	Stand	Prolonged sequential to large-patch mosaic	Likely at patch to stand scales with increasing drought and compound disturbances	Single to two-cohort depending on severity and scale of compounding disturbance

[a]Supported on the landscape under future, novel dynamics. Shorter reburn intervals for severe fire, compound disturbance (e.g., insects followed by fire), and non-indigenous insects and pathogens may limit opportunities for multi-cohort structures depending on archetype

as thinning to reduce drought stress (Bottero et al. 2017), reduction in fuel loading around older trees, or targeted insecticide applications to preserve threatened canopy species (Johnston et al. 2018; D'Amato et al. 2023b; Fig. 2) may be used to sustain these structures in the near-term, but may become challenging as climate change impacts and novel dynamics further evolve.

The challenge of applying the archetype models may become greater as ecosystems continue to move towards domains where no natural analogs exist (Fig. 3). For instance, changing habitat suitability will make it increasingly difficult to sustain native tree species that are already at their southern latitude or lower elevation range edges. In these instances, emphasizing species that are also native to the ecosystem and are predicted to have stable or increasing habitat with climate change may be warranted and consistent with the natural range of variation for composition of the ecosystem (Palik et al. 2022). In ecosystems where native adaptable tree species are lacking, considering assisted migration of functionally similar, climate suitable species may allow the characteristic disturbance regime associated with an archetype to be maintained. For example, in frequent fire forests (archetype 2) loss of a species with fuels that support the disturbance regime may be offset with regeneration of a better adapted species with similar fuels and ecological characteristics (e.g., Holbrook and Puhlick 2025).

Another challenge may be actual shifts from one archetype to another, for example, with shifts from lesser severity to greater severity of disturbance. For example, low severity frequent fire forests and woodlands may transition to mixed severity fire regimes with longer, more severe droughts, while the latter archetype may transition to an infrequent catastrophic regime. Similarly, forests characterized by a gap-based archetype may increasingly be subject to more severe wind disturbance resulting in structural conditions commonly associated with mixed severity ecosystems.

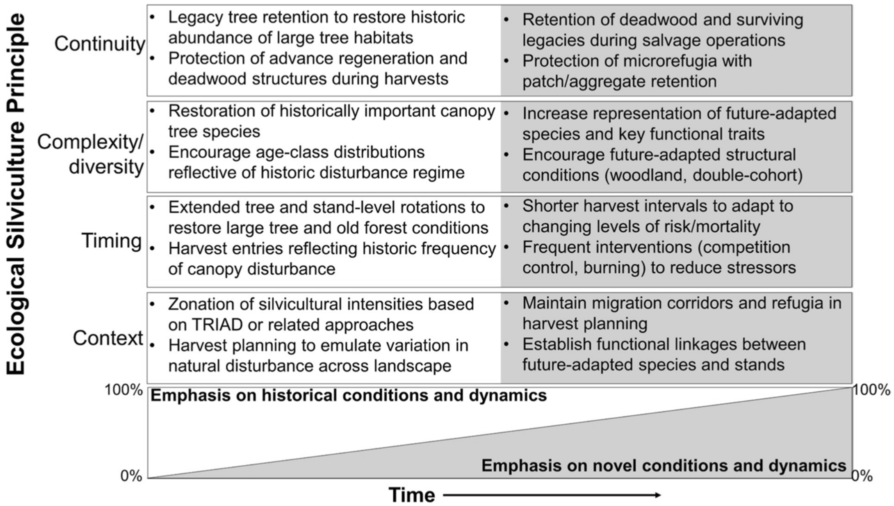

Fig. 3 Evolution in application of ecological silviculture principles as conditions become increasingly novel under climate change. Modified from D'Amato and Palik 2021

In addition to these transitions leading to new ecological states for ecosystems, they also will present challenges to managers as they decide how best to use an ecological approach for their silvicultural prescriptions.

Once ecosystems do move into novel domains, and silviculture becomes less effective at delaying such transitions, the foundational principles outlined above will still apply and, in fact, will become increasingly important for sustaining fully functioning ecosystems (D'Amato and Palik 2021). For example, sustaining deadwood dependent organisms or onsite carbon stocks argue for retention of large living and dead trees (*continuity*). In addition, the importance of these legacies in generating *climate buffered* microsites will only increase, particularly in ecosystems where temperature extremes and drought threaten to prolong preforest conditions. Managing for a diversity of tree species and tree sizes (*complexity/diversity*) may shift from native species to novel future-adapted species that can still sustain a suite of key functions (e.g., mast production, large-tree habitat).

The principle of *timing* in the context of adaptation is more complicated. Ecological approaches emphasize longer timeframes, i.e., rotations and cutting cycles; however, with climate change, developmental timeframes may accelerate, particularly disturbance return intervals and rates of ecosystem transformation. In some cases, this may result in a shortening of intervals between silvicultural interventions to adapt to these shifting dynamics, particularly in forests where mortality risks accelerate due to novel stressors (Nolet et al. 2014). At the same time declines in productivity and challenges to regeneration success may require lengthening of treatment intervals to allow for sufficient ecosystem recovery and development prior to the next intervention (Hogan et al. 2024). This may be particularly relevant at the preforest stage, where compounding stressors and novel dynamics extend its duration. Adaptive approaches to these changing preforest dynamics will depend on ecological, social, and management contexts. For example, are certain species, processes, or aesthetic values threatened or diminished to levels that call for more investment in regeneration practices to shorten this stage? Or are financial constraints and regeneration barriers too great, leading to acceptance of a prolonged preforest stage that may not provide all the values historically supported in a forest.

The degree of risk and cost associated with climate adaptive strategies, particularly planting of future-adapted species, may inform the *context* for how these approaches are applied in each landscape. Areas might be prioritized for more experimental and risk-laden practices based on vulnerability of forest values and functions to changing conditions. Intentionally planning to maximize linkages among stands in the landscape to support a diverse array of adaptive pathways would reflect an evolution of the principle of context that builds from the TRIAD approach of the balanced forestry era (Messier et al. 2019; D'Amato et al. 2023a).

Ecological Silviculture in the Climate Change Era

A challenge for silviculture with climate change may be acknowledging uncertainty in the specifics of future climates and associated forest dynamics, making exact models for silvicultural systems difficult to quantify. Still, we should not question whether the discipline of silviculture will continue to be on the front lines for addressing climate change. Silviculture conceptually is meant to be highly adaptable to changing conditions and diverse social, economic, and ecological drivers of change (Smith 1962), so adaptation in the face of climate change should not be viewed differently.

This said, an associated challenge will be maintaining social license to practice forestry despite climate change and the need for adaptation approaches. Stakeholders will continue to expect forests to be managed for diverse ecosystem services, including wood production (Peng et al. 2023). Increasingly, a growing number of these stakeholders also expect that an ecological approach will be used to meet their objectives for sustaining ecosystem services (Aguilar and Vlosky 2007; McGrath et al 2021) and for achieving third-party certification that acknowledges sustainable management (Palus et al. 2021). As we have presented here, such approaches often are based on natural models of forest development. It has been suggested that such an approach looks too much to the past and may be increasingly irrelevant in an era of rapid environmental change (Messier et al. 2015). Yet if there is a belief by society that an ecological paradigm is being replaced or even discarded, the social license to manage forests for a diverse array of services may be hard to maintain. The uncertainties and effects of climate change are challenging enough but navigating these with a limited social license to practice silviculture by diminishing ecological approaches would be self-defeating. Our view is that this challenge makes it even more important to incorporate an ecological approach based on natural models into silviculture, as this demonstrates that forestry continues to work to meet stakeholder's desire for sustaining diverse, multi-benefit forests that provide more options to sustain a full suite of services in the face of uncertainty.

The application of silvicultural strategies to sustain diverse values, species, and outcomes has underpinned ecological silviculture since its conception, with this foundation remaining central to addressing current and future challenges from global change. At the same time, ecological silviculture has grown from niche to mainstream over the past several decades, as evident in the numerous university courses and professional trainings that emphasize this approach, including the highly attended webinar series motivating the papers in this special issue (3,606 attendees; Horan et al., *this issue*). As such, a large and growing number of foresters and resource professionals approach forest stewardship through an ecological lens that applies ecological silviculture principles to achieve to diverse goals across a range of contexts. While we cannot predict what future sociopolitical or ecological dynamics may affect forests, we are confident that this shift towards a greater number of ecological foresters provides a powerful workforce to artfully address future uncertainties and challenges.

Acknowledgements We thank several influential thinkers in silviculture and applied forest ecology who helped shape our ideas including Bob Seymour, Jerry Franklin, Linda Nagel, Klaus Puettmann, Patricia Raymond, Christian Messier, James Long, Ellen Macdonald, and Craig Lorimer. We thank the managing editor and reviewers of the original manuscript for their helpful comments.

Author Contributions BJP and AWD equally conceived, designed, wrote this manuscript, and both approved of the final version.

Funding University of Vermont Rubenstein School of Environment and Natural Resources, USDA McIntire-Stennis Cooperative Forestry Program, USDA Northeast Climate Adaptation Science Center.

Data Availability There are no data associated with the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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