Journal of Forestry (2025) 123:133–160
https://doi.org/10.1007/s44392-025-00015-2

REVIEW PAPER

Silviculture—More Complex Than Ever

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Received: 25 March 2024 / Accepted: 15 August 2024 / Published online: 4 March 2025

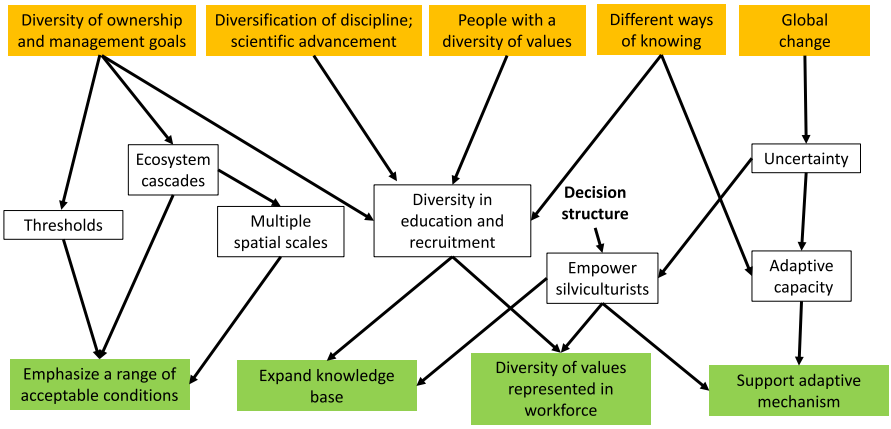
Abstract

Silviculture is the central discipline of forestry. It has always been influenced by changes in social and environmental conditions. Much has been accomplished in terms of advancing silviculture, including the culture, scope, and the goals and values it supports. However, we see that trends that initiated or strengthened during the last three decades are not well reflected in the current definition and this provides a barrier for further progress. Such trends include global change, an increased diversity of landowners and associated management goals, expectations of people with a wide range of values, and an acceptance of different ways of knowing. In this context, we see the benefit of providing a more holistic view. Thus, we propose to define silviculture as the "art and science of supporting and stewarding forest and woodland ecosystems and their ability to adapt in order to foster the diverse values of forest's contributions to people, including landowners, rights holders, communities and society". We discuss this proposed definition, specifically how it can lead to increased flexibility in silvicultural decisions, which can reflect a higher diversity of values and strengthen the adaptive capacity of forests. Furthermore, we discuss how addressing these trends requires a change in education.

Study Implications The opinion paper provides suggestions how to improve the ability of silviculturists to address challenges resulting from recent ecological and social trends. Educational programs will benefit from accepting a variety of human values as relevant to forestry, including other ways of knowing such as Indigenous knowledge. Much of this can be accomplished by recruiting students from diverse backgrounds and emphasizing the ability of students to work in a multi-disciplinary and multi-value settings. Similarly, management organizations will benefit when silviculturists plan their work in interdisciplinary and multi-scale settings that reflecting a populace with a wide variety of values, with a special emphasis on Indigenous stewardship. Changing assessment and planning procedures to emphasize the variability and thresholds will further increase the flexibility in the selection of silvicultural treatments. This flexibility is best used to modify silvicultural prescriptions so they reflect a wider range of values and strengthen mechanisms that support the adaptive capacity of forests.

Extended author information available on the last page of the article

Graphical Abstract



Keywords Adaptation · Workforce · Global change · Indigenous knowledge · Education

Introduction

Silviculture plays a central role in forestry as a link between the forests' ecological settings and the social and economic expectations people place on forests. Consequently, silviculture has always been influenced by and responded to changes in ecological, economic, and social trends (Puettmann et al. 2009). However, since the current definition (Box 1) was accepted more than three decades ago major changes are providing novel challenges. These changes include society's expectations of forests coupled with global change factors like climate change, biodiversity loss, land use change, and rapid spread of damaging biological agents. These and other issues also gained traction in silviculture applications and this development accelerated after the initial discussions about "ecosystem management" (e.g., Kessler et al. 1992). Since then, great progress has been made towards updating silviculture. For example, better integration of forest ecology, as well as an increased diversity of desired ecosystem services has resulted in the development of ecological silviculture, culminating in a specialized textbook (Palik et al. 2020). The types of practices that fall under ecological silviculture have been adopted by many public (for examples see supplement 1) and by private landowners (for examples see supplement 2 and Palik and D'Amato 2023). Also, examples of place-based stewardship efforts that are "rooted in Indigenous Knowledge (IK) and Western Science (WS)" (Forest Climate Adaptation Toolkit 2024). More recently, adaptive capacity is increasingly emphasized as a desirable outcome of silvicultural prescriptions in the face of current and predicted global change impacts (Puettmann 2011; Nagel et al. 2017; Ontl et al. 2019). There have also been inspiring initial efforts to broaden the knowledge

base and reflect a broader set of values (e.g., Himes and Dues 2024), especially as it relates to IK (e.g. DeLorey et al. 2022). Other advancements, such as in remote sensing technology and modeling procedures (Achim et al. 2022) provide opportunities for novel silvicultural prescriptions. It appears clear that a sole reliance on technical tools cannot be sufficient, but requires advancements in other aspects as well, e.g., in the art ("creativity" sensu DeRose et al. 2024).

Box 1 Selected definitions, as used in the manuscript

Silviculture, as defined by the Society of American Foresters (Deal 2018)*:Larsen

The art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis

The same definition was used by the International Union of Forest Research Organizations (IUFRO 2005)

Other definitions of silviculture:

The branch of forestry concerned with the theory and practice of controlling forest establishment, composition, and growth (Britannica 2024)

The branch of forestry that deals with establishing, caring for and reproducing stands of trees for a variety of forest uses (Canadian Encyclopedia 2024)

The practice of controlling the establishment, growth, composition, health, and quality of forests to meet diverse needs and values of landowners (UN-REDD 2024)

Reciprocity (in an Indigenous context)**:** "arising from the fundamental view that the Land generates and empowers life, including the non-material parts of life such as language, culture, and dream" (quote from and for more information, see Tapestry Institute 2024)

Right holder: Indigenous people with the right of self-determination, rights to education, health, self-government, culture, lands, territories and natural resources (Indian Law Resource Center 2024)

TRIAD: "'Triad' zoning divides landscapes into discrete units that emphasize reservation, extensive management, or intensive management" (page 1303, Betts et al. 2021; see also Seymour and Hunter (1992) for first application of the concept to larger forest landscapes and Himes et al. 2022 for more recent discussion of its utility)

*The oldest documents of the Society of American Foresters using the current definition that available to the authors dates to September 1994

The diversity of forestry professionals has increased in terms of gender, ethnicity, background, and values (Kern et al. 2019), although there is room for further improvement, especially as it relates to the organizational culture (Chojnacky, n.d.). We also see advancements in the increased diversity of educational pathways that can lead to employment in positions that develop and implement silvicultural treatments, even though college silviculture classes are almost exclusively offered within forestry programs. Recent discussions highlight that these trends and respective changes in the silviculture profession are very dynamic and to keep up with changes we need to maintain an ongoing dialog around the nature of silviculture (e.g., Jain 2019). Our (the authors') experiences in research, teaching, and interaction with people working on innovative silvicultural prescriptions also shows that the discipline would benefit from more strongly embracing current and anticipated social and ecological changes more formally. For example, the need for further discussions is partially reflected in recent publications in support of more western science emphasis (Achim et al. 2022). Responses to this suggestion have highlighted the need to also emphasize the "art" when developing silviculture prescriptions (DeRose et al. 2024).

At the same time, the notion of "control" (a prominent feature in the current definition of silviculture) is challenged by an increasingly unpredictable future (DeRose et al. 2024), as silviculturists are more and more frequently limited by the need to react to disturbances (Altman et al. 2024). Just as important, the notion of control is in conflict with other ways of knowing and relating to natural resources, e.g., the concept of reciprocity in Indigenous cultures (Kimmerer 2011). Finally, not all current trends are reflected adequately in educational materials, including textbooks (De'Arman and York 2021).

These and other debates highlight our conclusion that the current definition of silviculture used by the Society of American Foresters (Deal 2018, for other current definitions see Box 1; also, see past definitions in DeRose et al. 2024) being more than 30 years old do not adequately reflect recent trends. Despite selected recommendations in textbooks (Nyland 2016; Ashton and Kelty 2018) and notable efforts by many silviculturists to overcome this limitation, we have experienced the outdated definition to limit progress of the discipline (see also Holling and Meffe 1996). To better tackle the current and future challenges, we recommend updating the definition. This will be an indication and signal of the readiness of the field to embrace new challenges and eagerness to encourage a more holistic change in the culture of our discipline. In this context, we propose that silviculture is defined as:

> "the art and science of supporting and stewarding forest and woodland ecosystems and their ability to adapt in order to foster the diverse values of forest's contributions to people, including landowners, rights holders, communities and society".

Acknowledging the recent progress mentioned above, we justify our proposal for an updated definition by focusing on major recent trends that were not envisioned as very influential three decades ago. These include the increased diversity of ownerships and ownership goals and broader inclusion of people's values, especially from Indigenous Nations in decision making and recognition of treaty rights. Addressing global change issues, including higher uncertainty of future environmental, social, and economic conditions, has also become more urgent in the last three decades. These trends result in a need for increased diversity (of staff and values) in the silviculture workforce and associated changes in educational programs. These trends are relevant to all forest owners and right holders, but the specific impact and accordingly the need to address specific trends will vary across and within ownerships. For example, public ownerships might be impacted directly by changing public opinion when receiving feedback during their silviculture planning processes. Private landowners are likely impacted by the same changes indirectly through the public's support of selected politicians and ballot measures, altered consumer preferences, such as purchasing certified wood, or decisions around charitable giving. Last, we appreciate that these trends and associated changes are influencing the forest sector and profession in general. Here we limit our discussion to silviculture because it has a central role in forestry and thus can be viewed as a bellwether. Also, this allows us to stay within our expertise. However, we encourage other professionals to critically assess their discipline in this context as well.

To highlight the benefits of the updated definition, we align our discussion along the respective wording. Hereby, we not only focus on the new words, but also highlight how a modernized interpretation of words already in the current definition better addresses recent trends. We also acknowledge that selected trends and concepts are reflected in multiple parts of the definition. Wording is important and we do not want to "control" silviculture with the proposed definition. Instead, we hope to steward and foster the evolution of silviculture. Our explanation and interpretation of the proposed definition aims to empower silviculturists to advance the discipline to better deal with the variety of current and future trends. In the end, the success of silviculture will not be judged by its definition but by its ability to support forests and people.

Art and Science

Art and science have been viewed as parts of silviculture for over one hundred years (Society of American Foresters 1917). The need for both aspects and their relative importance has been subject to discussions over time. Recently, Achim et al. (2022) suggested that new technologies would provide so much detail and information that scientific approaches would be sufficient, and relying on art would not be necessary anymore. In response, DeRose et al. (2024) pointed out limitations of our scientific understanding, especially in the context of future uncertainties, novel conditions related to global change, and the need to bridge ecological and social settings. The authors suggested the benefits of relying on the "art." We also see the need for both and more importantly for a broadened interpretation of both concepts.

In this context, the trend towards an increased recognition of the diversity of landowners and rights holders, with an associated increased diversity of values and relations to the land is suggesting a need for an expanded interpretation of the art. In past discussions, art was mostly related to the experience, study, and observation by the silviculturists and team members (e.g., Pfeil 1851; Bundy 1999). Thus, the education, background, interest, and values of the silviculturists were reflected in the art. We propose that in this context art should reflect a broader set of values from a broader suite of people. First, art should acknowledge the impacts of forest management on all lands on a wide variety of environmental and social factors, such as global climate and public health (Hunt 2009; Karjalainen et al. 2010). Also, more members of the North America's society expect being able to provide input in determining acceptable and desirable silvicultural practices and being involved in decisions about the "social license to operate". Many public agencies and other landowners have successfully developed procedures to solicit public feedback as part of their planning procedures (e.g., Schneider et al. 2023). Similarly, silvicultural decisions on private lands are influenced by the public's experiences, observations, and values e.g., through political pressures and consumer choices (Aguilar and Kelly 2019; Wallius et al. 2023). The recent trend to view natural resource management as a coupled social-ecological system (Ostrom 2009) is another indicator of the benefits of allowing experiences and values of more people to contribute to the art (see also Diverse Values of Forest's Contributions to People below). Expanding the art to consider a wider set of worldviews

and values is thought to be key in moving toward a more just and sustainable future (Pascual et al. 2023; Raymond et al. 2023).

Integrating a wider set of worldviews has been discussed in the context of post-normal "science". Post-normal science encourages scientists to acknowledge and include information that is based on different value systems in the development and implementation of studies (Funtowicz and Ravetz 1991; Fig. 1a). Incorporating different people and values into research studies will encourage scientists to address questions relevant to and will facilitate communication with a broader populace. As a prime example of expanding the interpretation of art and science is integrating other ways of knowing. The discussion about the influences of a value system can benefit from tribal forestry, which has a long history of supporting tribal sovereignty and including cultural values in decision making processes and forest management. For most of the history of professional silviculture in North America, these values have been ignored or had limited influence.

However, there is a growing recognition of Indigenous rights (Dockry 2020) and the moral, ethical, and legal responsibilities to include tribes in forest management across ownership boundaries. For example, US federal and state policies are in place to consult with tribes on management (see the 2021 US White House memo on IK) and Federal Decision Making (Lander and Mallory 2021). There are also recent examples of co-management of forests between Indigenous and non-Indigenous peoples (Erickson 2023; Pinkerton 2019; Forest Climate Adaptation Toolkit 2024) and a recognition that Indigenous engagement is critical for these arrangements to achieve goals (e.g. DeLorey et al. 2022). Combining western science and IK provides a broader knowledge base for valuing and interpreting stand structure and composition and thus a broader foundation for silvicultural decisions (Kimmerer and Lake 2001, Fig. 1b). The recent Braiding Sweetgrass Report (Eisenberg et al. 2024) provides an overview and regional strategies that will be very helpful for silviculturists in this context. How exactly all these efforts play out in terms of expanding the "art and science" in silvicultural decisions will vary across different settings, e.g., on public (Erickson 2023), tribal (Mausel et al. 2017), and private lands (e.g., Campbell and Campbell 2017).

Supporting and Stewarding

The proposed definition uses the words "supporting and stewarding" instead of "control". Silviculturists have been aware for a long time that they don't have perfect control of forest ecosystems (e.g., Koestler 1949), even though silviculturists clearly have a strong influence on forest development. We do not see it as very productive to argue how much influence qualifies as control. Instead, we are focusing on the wording as it reflects how silviculturists view their role and relationship to nature. For one, the notion of control assumes that a problem is "well bounded, clearly defined, relatively simple, and generally linear with respect to cause and effect (page 329 in Holling and Meffe 1996). This "simple" view is tough to uphold in light of recent advancements in terms of our understanding of ecosystems as complex adaptive socio-ecological systems (Levin 1998; Ostrom 2009). It is directly opposed to

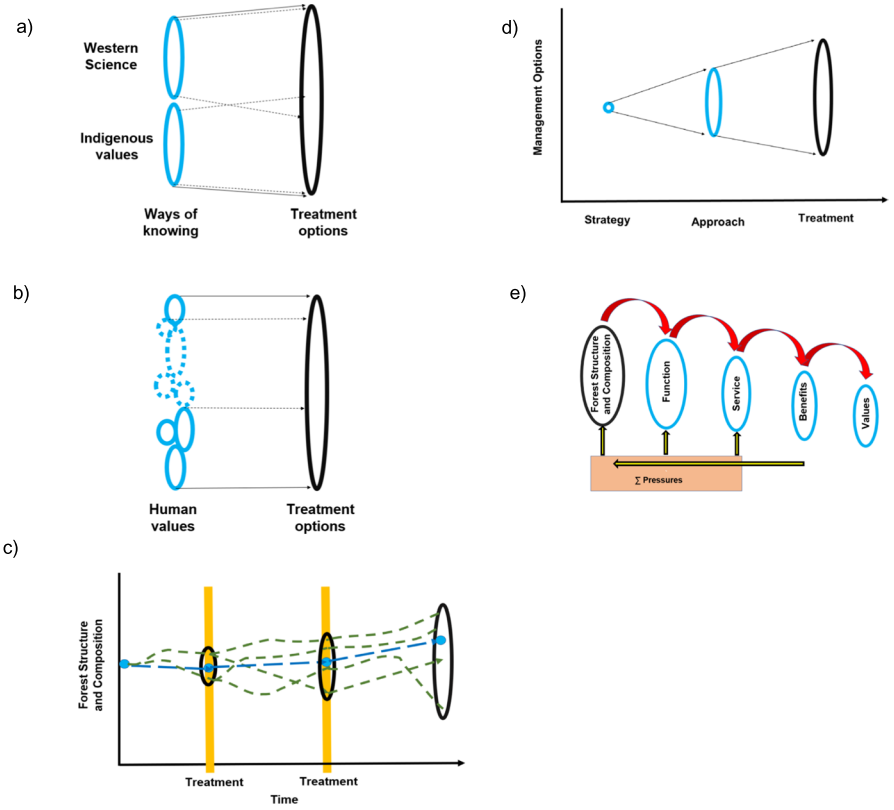


Fig. 1 Diagrams displaying how concepts discussed in the text can increase the diversity of possible silvicultural treatments, which can then be used to emphasize mechanisms of adaptive capacity (Table 1). **a** Combining the knowledge base of western science and IK (blue ovals) can lead to consideration of more management options (solid arrows, black ovals) than either one alone (dashed arrows). **b** Similarly, integrating a wider set of values (blue ovals) can lead to more management options than and relying on traditional "stakeholders" (dashed ovals). **c** Conceptual diagram showing a timeline with treatment options when managing for a specific target stand structure and composition (blue circle and long-dashed line). When stand development follows unpredicted patterns (green short-dashed lines) managing for an acceptable range of conditions can provide opportunities for more treatment options (black oval). Orange bars highlight when silviculture treatments are implemented (modified from Puettmann et al. 2009). **d** Conceptual diagram highlighting how hierarchical decision making (Sample et al. 2022) can empower silviculturists and increase treatment options. **e** Conceptual representation of the ecosystem cascade concept. Going up the cascades (red arrows), values can be provided by several benefits, which in turn can be provided by a multiple ecosystem services derived from various ecosystem functions. Ultimately, the variety of possible forest structures and compositions that provide the values allow for more option in silvicultural treatments and stand structures and composition (black oval), especially when the values are assessed at a landscape scale. Modified from Potschin et al. 2016

recent advancements in understanding natural resources issues as wicked problems (DeFries and Nagendra 2017; also see discussion of People, including Landowners, Rights Holders, Communities and Society).

Examples of the implications of using the word "control" include an inherent mismatch with adaptive management, which accepts that forest development is

unpredictable and management changes have to be made along the way. Also, as control implies a top-down influence (for a discussion of resulting problems, see Holling and Meffe 1996). Instead, we propose that silviculturists view their role as "supporting and stewarding" forests and woodlands. For one, this emphasizes that the interplay between natural and human aspects is bi-directional, i.e., includes reciprocity, a key concept in Indigenous relations with the land. In addition, it reflects broader ethical and moral discussions about human relations with the natural world in general (Muraca 2011, 2016; Raymond et al. 2023; Himes et al. 2023).

Such a difference in viewpoint can show up on the landscape in terms of tree regeneration. "Controlling" silviculturists likely replant patches with seedling mortality (in some cases multiple times). "Supporting and stewarding" owners would accept a certain amount of un- or under-stocked area in plantations as a way of accepting self-organization of an ecosystem. These patches may be biodiversity hotspots in an otherwise homogenous plantation. The additional cost of controlling the factors that lead to seedling mortality and replanting, in conjunction with the replanted seedlings' slower growth when weed control practices are optimized for the original planting, increases the likelihood that the majority of those replanted seedlings will not become crop trees. Instead, they can be harvested as part of a (low) precommercial or commercial thinning. Thus, for the patches with tree regeneration challenges, not replanting not only greatly reduces the workload for silviculturists, but may not lead to (significant) economic losses (Puettmann and Tappeiner 2014).

The new words further reflect a certain humbleness in terms of our ability to manage forest land for a specific set of conditions. Instead, it acknowledges that natural processes, especially disturbances, play an influential role. Ignoring or replacing them with silvicultural treatments can have negative implications (Long 2009). We also base our new wording on complex system theories and highlight the implications of this using the panarchy model. Compared to stand dynamics or general successional models, the panarchy model highlights the cyclic nature of ecosystem development with a specific emphasis on the importance of disturbances (release) and the subsequent recovery (bottom-up reorganization) phases. Many natural adaptation mechanisms that play out during these phases (for examples see Table 1, Gunderson and Holling 2002) have been ignored as silviculturists replaced natural disturbances with reforestation and density management practices. For example, reproduction cuttings and nursery and planting efforts (as controlling efforts) replace many natural factors driving the adaptation during the release and reorganization phases (Table 1). Assessing how management practices can be modified to achieve management goals, such as revenue production, while at the same time strengthening adaptive capacity can be found in Drever et al. 2006, Messier et al. 2013, and Palik et al. 2020; see also "Ability to adapt" below).

Supporting and stewarding also means encouraging the adaptive capacity of forests (Puettmann 2011, D'Amato and Palik 2021). Silviculturists can now take advantage of the results of novel planning tools, such as scenario analyses and strategic foresight methods (Karjalainen et al. 2010, Bengston 2019). For example, public and private landowners can investigate how they see forests developing with and without different types of disturbances. They also can explore the impact of changing social expectations, and political changes. An example of

Table 1 Examples of different organizational levels and associated adaptation mechanisms highlight the wide range of opportunities how silvicultural treatments can influence adaptive capacity. For forestry operations, the measurable properties could be used as criteria to assess management operations. Adapted and modified from Conrad (1983)

Organizational level	Measurable property	Adaptation mechanism
Biota	Species composition	Migration, Extinction, Speciation
	Food web structure	Different routes and rates of energy and matter movement
Population	Number of organisms	Flexibility in reproduction rates, social structures and relationships
	Spatial locations of organism	Social plasticity, Movement
Organism	Number and size of bodies and organs, relative position of organisms	Developmental plasticity (e.g., muscle, leaf area, size
		Physiological plasticity Behavioral plasticity
Genome	DNA sequence	Gene pool diversity

legal constraints that have a great impact on silviculture are the three or five-year regeneration requirement for all non-federal forest lands in Washington and Oregon, respectively, and following certain regeneration harvests on non-federal lands in Maine. Other examples of administrative or social drivers include when subsequent treatments cannot be implemented as planned due to budget cuts. Integrating the option of unexpected developments into the management plans may require changes in policies and extra educational and collaborative efforts to gain public support and adoption by forestry professionals (Himes et al. 2023). This can increase profitability in the long run, especially as disturbances are predicted to become more frequent and intense in the future (Montagné-Huck and Brunette 2018). Providing support and stewarding (versus control) implies that managers acknowledge and plan with certain risks (Aplet and Mckinley 2017). Thus, silviculturists can prepare by ensuring the flexibility to implement unplanned silvicultural treatments in response to unforeseen development (see discussion about adaptive management in Walters 1986).

Accepting and planning with risks and uncertainties can create challenges when relying on traditional predictive tools to support silvicultural decisions. Most simulation models are deterministic which assume control and constant growing conditions. If other tools, e.g., stochastic models, are not available, silviculture decisions under novel global change conditions can only rely on the art. Then decisions will then be based on personal experience and other scientific information relevant to basic ecological understanding of forest development. Also, including IK has been suggested to be valuable in this context (Lemi 2019; Hallberg-Sramek et al. 2023). This approach is better reflected by choosing supporting and stewarding. Regardless of which model type or tool is used, shifting the emphasis from a central trend, e.g., the predicted mean value, to the variation around that trend will be more helpful

when considering a range of acceptable outcomes as management goals (Fig. 1c). Accepting a range of outcomes allows silviculturists more flexibility when responding to stand development trends. In this context, emphasizing the variability of and non-linearities in ecosystem responses is crucial for determining tipping points or thresholds (Mellert et al. 2015). For example, in addition to learning about the most likely profit, understanding the chances of not reaching a lower threshold is crucial to avoid bankruptcy of commercial forestry operations (Taleb 2020). To be successful, this requires intensive monitoring and a management structure that provides the flexibility to apply modified treatments in a timely manner (Werners et al. 2013; see also discussion about hierarchical decision making below).

Forest and Woodland Ecosystems

We maintain the words "forests" and "woodland" from the current definition but in their interpretation emphasize the broadening of the settings and goals relevant for silviculture. For example, our interpretation of woodlands emphasizes among others the benefits of more open conditions (Swanson et al. 2011) and expands the interpretation in the context of biodiversity and disturbances (Hessburg et al. 2015). In addition, we added "ecosystems" to the definition as a way to shift the emphasis away from trees (stands) and to include all other ecosystem components relevant to forests and forestry. We see this as encouraging silviculturists to include these and related concepts more formally in silvicultural decision making. This also acknowledges ecological shifts that may occur following disturbance as the climate changes or new invasive species take over (Falk et al. 2022; Seidl and Turner 2022).

At the same time, the traditional focus of silviculture on stand-level decision making can result in viewing the increasing diversity of ownerships, values including relations with the land and associated goals as a hindrance. While inventories and treatments may still be applied at stand scales (O'Hara and Nagel 2013), expanding the scope of silviculture more formally to larger spatial scales, such as landscapes, has been discussed for a while (Franklin et al. 2018). Understanding that this is not new to silviculture, we still see the benefits of focusing specifically on aspects "beyond the stand " that provide more flexibility in silviculture decisions. For example, if the overall goals are achieved at a landscape level, the deviation from the mean found in individual stands can be viewed as an opportunity to enhance adaptive capacity if it is acceptable at relevant larger scales (also, see discussion about simulation models above). This will allow for more diverse stand conditions and developments and associated flexibility in decision making (Puettmann et al. 2009, Fig. 1c). Switching scales provide more flexibility to accommodate other values and goals at the stand level. It is important to note that silviculturists can glean good information from the discussion of these issues in regard to forest restoration efforts (Bullock et al. 2022) and landscape-level restoration programs in the USA (Schultz et al. 2012; Franklin et al. 2014; Lake et al. 2018).

Expanding the scope of silviculture to larger scales is also reflected in the recent discussion about landscape resilience (Messier et al. 2019), the TRIAD (Côté et al. 2010; Himes et al. 2022), and land sharing/sparing (Betts et al. 2021) approaches as opportunities

to minimize conflicts and explore a synergy of the different ownerships. In places, the TRIAD could be modified to help achieve goals that cannot be achieved at the stand or ownership scales, e.g., habitat conditions for species with larger home ranges (e.g., Cederlund and Sand 1994; Forsman et al. 1984). Other ideas to integrate multiple ownership goals and expand silvicultural options include the Anchor Forests idea that would have tribal forestlands and forest management infrastructure "anchor" the regional forestry economy by ensuring the future ability to harvest timber on a variety of ownerships (Corrao and Andringa 2016). Even forest owners with fairly narrow management objectives are more and more forced to acknowledge the larger implication of their silvicultural decisions, such as investment companies which own land in a city watershed (for example, see supplement 3).

Landscape level planning approaches clearly have challenges and provide examples that any changes in silviculture cannot be viewed in isolation but needs to be supported by changes in the larger political setting. For one, any top-down approach to the role of different owners or stands within a landscape will benefit from integrating concerns of local populations (Andersson et al. 2015; Bredemeier et al. 2015). Another challenge is that the management goals, and thus to a degree also the silvicultural practices, are often already "mapped" on the landscape by current ownership patterns. In places, a TRIAD type management plan can provide opportunities for landowners focusing on a narrower set of goals (e.g., Côté et al. 2010), e.g., private landowners that emphasize income maximization. If that is not sufficient to account for economic inefficiencies, potential approaches to increase the management flexibility and accommodate landscape level goals include financial incentives to private owners, such as easements, subsidies, or zoning regulations (Binkley 1997; Resch et al. 2023). Alternatively, management goals can be indirectly influenced by policies, e.g., restriction of selected silvicultural practices or influencing of market preferences or trade policies. The Good Neighbor Authority and Tribal Forest Protection Act programs of the USDA Forest Service are examples of how forest management organizations can be set up to collaborate across ownerships and jurisdictions to work beyond stands and ownerships boundaries to achieve larger scale goals.

Silvicultural decisions have also benefited from considering spatial scales smaller than the stand. This approach is based on an improved understanding that many ecological processes act at smaller spatial scales, e.g., disturbances (Spies et al. 1990), regeneration (Coates 2002; Dodson et al. 2014), and competition and facilitation (D'Amato and Puettmann 2004), with implications for stand structures (Peck and Zenner 2022; Windmuller-Campione et al. 2022). This has been a major factor in encouraging the development of ecological silviculture (Seymour et al. 2002; Palik et al. 2020), close-to-nature forestry (Schűtz 2011) and similar approaches. Many of these approaches emphasize within-stand heterogeneity in structural and composition conditions with resultant impacts on resource distributions, habitat conditions, vulnerability to disturbance, and pathways for adaptive response (e.g., see Wikle and D'Amato 2023, and citations therein). However, we still see the benefits of formally appreciating that management units (stands) that are not "uniform" often strengthen more natural adaptation mechanisms (Table 1), while at the same time provide more flexibility to accommodate natural trends and how to achieve selected management

goals (Messier et al. 2013, Table 1). In cases, allowing natural trends to develop rather than fighting them can provide savings. Examples include areas with regeneration challenges that may have to be replanted (in cases multiple times) to achieve homogenous stocking (Puettmann and Tappeiner 2014).

Ability to Adapt

Inclusion of the phrase "ability to adapt" acknowledges and emphasizes ongoing challenges due to global change and increasing uncertainty facing forests and woodland ecosystems. Compared to 30 or more years ago when the current definition was drafted, now there is general agreement in the profession that global change impacts are one of the major factors impacting the forests' ability to provide ecosystem services (Seidl et al. 2017; Himes et al. 2023). Global change factors play out at various organizational levels, from the global (Forzieri et al. 2022) to the individual tree level (Hartmann et al. 2022), suggesting the need for forests to adapt at all organizational levels (Table 1). The increasing impacts of these novel challenges in conjunction with an increased demand for ecosystem services, e.g., carbon mitigation (Lippke et al. 2021), suggests an increasing need for silviculturists to strengthen the forests' ability to adapt to changing and in many cases novel environmental conditions (Puettmann 2011; Puettmann and Bauhus 2023). In this context, adaptive capacity can be viewed as a supporting ecosystem service, as it is necessary to ensure supply of all provisioning, regulating, and cultural ecosystem services (GLIFWC Climate Change Team. 2023). As such, ensuring and increasing the adaptive capacity through silviculture deserves a special emphasis and is thus included in the proposed definition.

As a supporting ecosystem service, adaptive capacity will take on higher priority over time as a fundamental component of ecosystem service bundles (Spake et al. 2017). Few—if any – ecosystem services can be provided sustainably at desired levels, if forests are not adapted to thrive under current and future conditions.

Efforts to deal with global change will be most efficient if they are addressed at multiple scales (see above) and organizational levels (Table 1). For efficiency, all silviculture manipulations are best viewed as an opportunity to maintain or increase the adaptive capacity. This includes practices originally developed to achieve other goals. As an example, the thinning practice was developed with timber productivity in mind (Puettmann et al. 2009). It can be modified to increase the adaptive capacity of forests (Drever et al. 2006) by increasing and diversifying understory vegetation (Neill and Puettmann 2013), enhancing soil moisture availability (Bottero et al. 2017) or the spatial variability of trees (Churchill et al. 2013). Associated benefits such as limiting vulnerability to selected disturbances may well be worth the impact of such modifications on the income (Palik et al. 2020). As another example, live tree and deadwood legacies have traditionally been viewed in the context of life-boating for wildlife species (Rosenvald and Lohmus 2008, Gustaffson et al. 2012). They can also be viewed in the context of increasing adaptive capacity (D'Amato and Palik 2021, also see Brang et al. 2014) by enhancing short-term management flexibility. For example, leaving merchantable trees in harvesting operations may lead to lower short-term profit, but can make future

unplanned entries commercially feasible. This may be helpful or critical for example on private lands, if such unplanned treatments are needed to prevent forests from developing in an unacceptable direction and other financial resources are not available. As described above, such changes in silvicultural practices aimed at maintaining or strengthening the adaptation mechanism (e.g., Table 1) can only be successful over the large scale and long run if they are economically feasible and go hand in hand with efforts to involve and thus gain support by the broader public (Himes et al. 2023).

Emphasizing adaptive capacity also requires more information to be integrated into silvicultural prescriptions than has traditionally been used. Several forestry owners now use information from the formal vulnerability assessment summarized in Ontl et al. (2019) when developing silvicultural prescriptions. At regional or landscape scales, other aspects provide insights that can be incorporated into silvicultural decisions, such as fire refugia or climate refugia (Meddens et al. 2018; Krawchuk et al. 2020). Indigenous communities are also creating vulnerability assessments and adaptation strategies based on cultural values and IK (TAMT 2019, GLIFWC Climate Change Team 2023). These practices will be more effective in changing silviculture when they become standard for a broader section of landowners. Also expanding the vulnerability assessment into more formal scenario analyses will be beneficial. Scenario analyses are designed to consider a broad suite of factors that influence forest management, including global issues and social trends (Glorioso and Moss 2011).

Another aspect worthy of consideration when managing for adaptive capacity is to acknowledge the role that outliers or extreme events play in shaping the forest (Puettmann 2021). In the past much emphasis has been placed e.g., on the mean fire return intervals. Instead emphasizing the variability of such events, relationships, and ecosystem responses will be more needed in the future, especially because of the complicated statistical implications of the occurrence of extreme events (Puettmann 2021). Understanding and planning with the inherent variability and extreme events is crucial not only to determine the range of acceptable long-term outcomes (Fig. 1c). In addition to developing a silviculture plan that ensures the highest short or long-term profits, is crucial to consider that events push a landowner below acceptable thresholds along the way. A plan that maximizes income over the long-term is not useful, if a landowner goes bankrupt in year two (Taleb 2020; Puettmann 2021).

Utilizing theories from complexity science can be helpful in a future with higher variability and uncertainty (Messier et al. 2015), especially as they relate to decision-making processes and criteria as described above. The shift from a top-down control approach to stewarding self-organizing processes will benefit from "pushing silvicultural decisions down" organizational hierarchies to the people closest to implementing the decision (Malik 1984). Giving silviculturists greater decision authority not only allows them to refine silvicultural description to the specific local set of environmental, social, and economic conditions at the time (and not as they existed at the time when management plans were developed). It also ensures shorter feedback loops, as unexpected developments are then efficient opportunities to learn and modify silvicultural practices accordingly (Walters 1986). In this context, formally viewing silvicultural decisions in the hierarchy of strategies, approaches, and treatments (Sample et al. 2022, Fig. 1d) may provide practitioners with more guidance regarding the multiple possible treatment options that are available to influence

the adaptive capacity of forests. In this model multiple approaches can achieve individual strategies and multiple treatments are embedded in individual approaches (Fig. 1d), resulting in better opportunities to provide more management flexibility and accommodate local conditions.

Diverse Values of Forest's Contributions to People

Inclusion of the phrase "diverse values of forest's contributions to people" recognizes numerous ecosystem services and relations with the forest. Reflecting its origin during times of wood famine, initial efforts during the development of western scientific forestry as a discipline were mainly focused on provision of wood products (Hawley 1921; Mantel and Hauff 1990). Today, meeting multiple goals or objectives in a single silvicultural prescription has become commonplace in silviculture discussions and textbooks (e.g., Nyland 2016; Ashton and Kelty 2018). This is especially evident on public lands (Long et al. 2010) but also on many privately-owned woodlands (Snyder et al. 2019) and on industrial and investor-owned lands, even when those owners prioritize financial returns. The increased diversity of landowners (see below) and the parallel increase in diversity of public values related to forests (McFarlane et al. 2011) in the last decades provides novel challenges and prompts us to add extra emphasis to this topic. The impacts of this diversification are typically only controversial when goals, values, or priorities are in conflict. Goals, such as sustainability of selected wildlife habitat may be in sync with recreational or cultural goals, or even on-site carbon storage goals, so-called ecosystem bundles (Spake et al. 2017).

Alternatively, many of these goals could be in direct conflict with objectives to maximize short-term revenue or limit access to sacred sites and interfere with treaty rights. Popular textbooks provide an indication of how silviculture as a discipline has responded to the expansion of the number of goals. North American silviculture textbooks have separate chapters that address unique practices when foresters have specific goals (Nyland 2016; Ashton and Kelty 2018). Alternatively, other silviculture books are uniquely tailored to a specific set of management objectives (e.g., Shepherd 2012; Palik et al. 2020) or stand structures (Schűtz 2001). We find similar approaches in silviculture education with selected programs that offer a single silviculture class for all forestry students. Other programs have two or more classes, each focused on a narrower set of ecological, social, or economic goals.

One approach to dealing with integrating potentially conflicting management goals is to implement silvicultural practices that minimize trade-offs rather than optimize a single outcome (Bradford and D'Amato 2012, Himes et al. 2020). Another option is to focus silvicultural activities on providing a bundle of compatible ecosystem services (Deal et al. 2012). Alternatively, zoning forest land (Resch et al. 2023) to provide compatible bundles of ecosystems where they are most important or can be produced most efficiently through divergent silvicultural practices can lead to efficient provision of a wide range of benefits at large scales (Himes et al. 2022). Regardless of the strategy employed to minimize trade-offs between different ecosystem services and provide the most (overall) benefits of forests, decisions by landowners and society about the relative importance of different ecosystem services will likely be required.

Navigating these relative values provides limited options when landowners rely on a single indicators of value (e.g., money) or have a relatively narrow management focus, such as on industrial and investor owned lands. More options are available when landowners and the public value the diversity of ways that forest benefits are important to people. For example, some Indigenous communities in the United States are reconceptualizing forest management as management based on cultural values and "first foods" to promote sustainable forest and natural resource management (Quaempts et al. 2018; GLIFWC Climate Change Team 2023). Recent efforts using tribal consultations and other ways, such as co-management, aimed at integrating Indigenous values into management decisions (DeLorey et al. 2022) are efforts in the right direction. The value of such efforts is highlighted by Termansen et al. (2022), who identified more than 50 distinct valuation approaches, many of which are rooted in Indigenous beliefs.

People, Including Landowners, Rights Holders, Communities and Society

We suggest broadening the definition to acknowledge the broader set of relationships between all people and forests by using the phrase "people, including landowners, rights holders, communities and society". For one, in the past people had a different appreciation for the role forests and forestry play in terms of their well-being and good quality of life, e.g., regarding wood as fuel or energy source (Arnold et al. 2003). By the later part of the twentieth century timber was, at best, a secondary concern for many Europeans when they thought about forests in general (Rametsteiner et al. 2009; no similar data exist for North America).

The range of people directly impacted by silvicultural decisions has expanded. For example, during the 2021 and 2023 fires, people living in the eastern US, including in New York City, were directly impacted by smoke from forest fires in the western US and Canada, respectively (Sever 2022; Bartels 2023). Thus, the "clientele" (for lack of a better word) is expanding way beyond people traditionally interested in the forestry sector and their values and attitudes may change over time, e.g., after being exposed to smoke. Obviously, we do not propose that all "clientele" will be directly involved in silviculture decisions in all or even most settings. But having a clear understanding of values that the diverse set of people have and derive from forests can better inform the implications when forest structure and composition are manipulated.

Emphasizing the values people derive from the forest also provides opportunities for exploration of more flexibility in silviculture decisions, which then can be used to encourage e.g., adaptive capacity. The ecosystem service cascade concept (Potschin et al. 2016; Fig. 1e) highlights that specific values may be satisfied by more than a single ecosystem service and one set of stand conditions. Thus, the concept encourages silviculturists to consider whether a wider range of stand structures and compositions will satisfy a particular value (Fig. 1c). We propose that more investigations into these relationships are essential, especially when the desired values appear to be in conflict. In this context, our profession will benefit when silviculture research is an integral part of cross-disciplinary projects, e.g., to gain a better understanding of linkages between forest stand structure and composition (i.e., biophysical structures and

processes that make up ecosystems), ecosystem functions, services and relationships with people involved and the types of values they reflect (DeFries and Nagendra 2017). This is especially relevant regarding the issue of whether e.g., different ownerships or relations with the land can more efficiently provide a selected set of ecosystem services (see discussion about TRIAD and land sharing/sparing above).

Existing models of forest development with explicit links to a wide range of values through efforts of focused research integrating silviculture studies with social science studies will be helpful in the future (Sotirov et al. 2019). For instance, participatory mapping approaches could help identify relationships between forest structural and compositional components and a diverse array of values (e.g., intrinsic values assigned to the forest, values derived from relational experience in the forest, values derived from recreation, and others; Brown et al. 2020). Another avenue is to engage people impacted by forest management in deliberative evaluations of different silvicultural scenarios (Hallberg-Sramek et al. 2023; for examples on private lands, see supplement 3). Ideally, a range of conditions can be identified which support diverse values that allow for integration of flexibility into silvicultural decisions. Exploring this flexibility is a powerful complement to the flexibility gained when shifting the focus from stand-level to landscape-level assessments, as discussed above (Fig. 1c).

In the US, other novel types of owners have acquired forest lands in the last decades since the current definition of silviculture was written, including Real Estate Investment Trusts and Timber Management Organizations. Because of the short-term planning timeframe and the narrow focus on economic gains on these two ownerships, it is especially challenging to convince their silviculturists to address issues we highlight with our proposed definition. Even though their lands are not immune to the trends that encouraged us to push for the new definition, any changes will have to fit within their management constraints. In cases, easements that encourage selected silvicultural practices have been effective as economic incentives. Also, selected investment companies explore the carbon market with associated implications on other ecosystem services or advertise their environmentally-friendly management approach. We assume that such progress will continue as the impact of recent trends become stronger.

On the other end of the landowner spectrum are shifts in non-industrial private holdings, including those now held by minorities (Butler et al. 2020), a more urban populace, non-profit organizations, community forests, and public ownerships. These landowners often place more value on biodiversity, wildlife habitat, recreation, and carbon storage (Snyder et al. 2019), while still considering economic constraints. On these ownerships, carbon storage is gaining more interest as a nature-based solution to climate change and a way to compensate landowners for this ecosystem service and associated co-benefits (Lee et al. 2018). New developments, such as biodiversity credits (Rao et al. 2024), will provide more opportunities for all ownerships in the future. Our proposed definition will help prepare silviculturist to take advantage of these opportunities.

Diversity in Workforce and Education to "Implement" the New Definition

Changing a definition by itself will not be sufficient to effectively deal with all future challenges. Addressing these issues requires a culture driven by silviculturists whose qualifications and interests reflect the wide variety of disciplines and values relevant to forests and forestry. It is well recognized that increased diversity in the discipline has benefits, including bringing in a broader variety of ideas and viewpoints, increasing public trust by including representation of a broader set of the public (Westphal et al. 2022), and empowering groups, such as female forestry owners (Hamunen et al. 2020).

In regard to integrating more "diversity" in silviculture education, expanding the forestry programs beyond traditional forestry classes, and fields e.g., by including restoration ecology and Indigenous relations, lowers barriers for students and encourages interactions of faculties working in the various subdisciplines. It also allows students to be exposed to a broader set of ideas, thinking, terminology, and values. Also, an associates degree still provides a potential entry point into many silviculture positions. This creates more opportunities for recruitment, including increasing the options for students to obtain a forestry degree who may not have the opportunity to enter a four-year forestry program right after high-school graduation. Already many four-year university programs are emphasizing the option to transfer in from community colleges. Accordingly, any support for forestry programs at e.g., Tribal Colleges, "outstate" universities, community colleges, and high schools can help alleviate some social justice issues. Finally, in all educational programs it may be helpful to expose students to different career paths that can lead to silviculture positions, e.g., through targeted internship and mentorship programs.

As educational fields diversify, silviculture appears to be one of the last holdouts within a narrow setting, as undergraduate classes and graduate degree programs in silviculture focused mainly on students enrolled in forestry programs. This provides recruiting challenges to entice students from a broader background into the silviculture field. Thus, silviculture positions are often filled with graduates that received their training in forestry programs. While these people are typically highly qualified in the silviculture discipline, recruiting from a narrow set of colleges has allowed selected educational programs (and instructors or advisors) to have a large "footprint" in the makeup of the silviculture profession. Thus, ideas, approaches, and values of many silviculturists and also their ability to work in interdisciplinary settings were imprinted by a few programs and people. Changes in hiring procedures and efforts to diversify faculties have helped in this regard. In addition, more recent activities will help broaden the exposure of students within the field of silviculture. For example, silviculture seminar series that expand the suite of presenters to include people from different regions, value systems, and expertise, including presenters from related or "not-so-related" disciplines.

Silviculture is a keystone class within accredited undergraduate forestry programs. In such settings, silviculture classes typically require a set of prerequisites. This limits them to upper-level forestry and natural resource management students. By restricting silviculture to only a narrow group of students, classes are not bringing together the full range of individuals who will be working in the forestry sector and thus is continuing to create disciplinary isolation. To counter this, forestry programs may want to expand capstone courses, bring together students from a variety of programs, including from the social sciences (Puettmann et al. 2016). Especially for silviculturists an emphasis in such classes on learning how to work in multidisciplinary team will be valuable. Also, these courses are especially helpful in diversifying the exposure of forestry students by requiring collaborations with students who may not have taken any forestry classes previously. An alternative approach discussed recently is that forestry specialization into subfields, like silviculture, would be implemented at the graduate-level and associate-level, while the bachelor-level contains more broad interdisciplinary learning opportunities (Sharik et al. 2020).

The central role of silviculture as an integrating discipline also suggests that silviculture classes could be modified to be suitable for "onboarding" of graduate students that come from other disciplines. This, can provide for stimulating discussions that benefit all students with a conventional forestry background (K. Waring, K. Puettmann and M. Windmueller-Campoine, personal observations). Educational programs will also benefit from selecting case studies, field trips, and guest speakers specifically as opportunities to feature the challenges and benefits of the integration of various disciplines, including social sciences and planning. Doing so will prepare students for collaboration in diverse groups and also provide more opportunities to highlight contributions from members of underrepresented groups and different cultures (Allen and Collisson 2020; Dockry et al. 2022).

Over time many forestry programs, agencies, and management organizations have become more comfortable hiring silviculturists from a broader pool than derived from forestry programs alone. The resulting diversity of ideas, research and management approaches, assumptions, and values provides a starting point for better interdisciplinary collaborations and appreciation of a broader set of values. Similarly, many faculty and staff at educational institutions received their disciplinary training in programs other than forestry. In both settings, these employees benefit from special "onboarding" efforts, which is a great opportunity for cross-disciplinary "fertilization" to silviculture programs, as described above. For example, special workshops or classes, such as the National Advanced Silviculture Program, aimed specifically as both continuing education and an "orientation" of people from other disciplines by highlighting linkages and opportunities in forestry. Similarly, other endeavors, such as the Northwest Innovative Forestry Summit (NNRG 2024) emphasize peer-to-peer sharing and community building. Such efforts encourage silviculturists to be tied into groups of people with diverse values and expertise, including Indigenous nations.

Positioning silviculture in an expanded context may also make it more attractive and accessible to a broader set of people. Especially the recent increased interest in restoration and adaptation has provided opportunities for silviculture to "come out of its forestry corner" and actively explore opportunities to expand into new

directions that reflect recent student interests (Sarr et al. 2004; Grossnickle 2016). A variety of organizations beyond those traditionally focused on forestry operations and thus have a history of employing silviculturists are now dealing with restoration and/or adaptation challenges. Such organizations include public agencies, but also selected woodland owners and environmental organizations.

Positive examples of continuing education efforts for silviculturist include that recent classes in the National Advanced Silviculture Program contained students from across a wide demographic, e.g., in terms of age, number of years in Bureau of Indian Affairs, USDA Forest Service, or Bureau of Land Management employment, locations, and types and place of education. Other programs such as Forestry for the Birds are now delivered across much of the US provide opportunities to bridge disciplinary boundaries by exposing birders to silvicultural decision making. At the same time silviculturists gaining a better appreciation of how their decisions influence birds, a topic that has gained attention even on industrial and investor owned lands (Betts et al. 2013).

Past strategies of attracting a broader diversity into the workforce in general, including silviculture, have been successful (Balcarczyk et al. 2015; Haynes and Jacobson 2015; Locke et al. 2023). But facilitating the "infiltration" of this diversity into organizational structures and cultures requires a combination of changing hiring and promotion practices (Sachdeva et al. 2023) and continuing education of the existing workforce. Such efforts need to include student internship programs specifically designed to bring students from underrepresented and marginalized communities into silviculture programs and positions (Dockry et al. 2022). Thus, despite improvements in terms of diversifying the workforce, changing the culture in forestry organizations towards innovation requires more effort and time (Kern et al. 2019). Even after implementation of many programs and special hiring efforts, changes in staffing are not automatically reflected in a culture of innovation, open-mindedness to a diverse set of values and change (e.g., Chojnacky n.d).

Special challenges exist to engage Indigenous peoples in silviculture and integrate Indigenous historical and contemporary ties to the land (e.g., Mausel et al. 2017), global Indigenous stewardship of biodiversity, and other aspects of IK in shaping novel silvicultural strategies to confront global change (e.g. M'sit No'kmaq et al. 2021). To engage Indigenous communities programs must recognize and respect Indigenous sovereignty and support Indigenous goals for forest management (e.g. IFMAT 2023). Engagement with Indigenous communities also needs to follow ethical data and research practices (see Matson et al. 2021; Carroll et al. 2020). Other opportunities include strengthening forestry programs at Tribal colleges and ensuring that educational programs are offered in locations easily accessible to Indigenous populations.

Concluding Remarks

Just like the current definition has not prevented silviculturists in places from addressing novel challenges, a new definition by itself will not overcome those challenges per se. But updating the definition to reflect the changes that occurred during

the last three decades will send a strong signal that the silviculture profession is getting ready and eager to deal with the variety of current trends and associated complex challenges. Our interpretation of the wording (including words already in the current definition) highlights how the updated definition can be "translated" into an updated work culture. We see the following potential outcomes of embracing and implementing the new definition. First, silvicultural prescriptions provide for more flexibility when they are not focused on achieving a narrow, desired future set of stand conditions. Instead, an increasingly unpredictable future requires silviculturists to accept variability, uncertainty, and self-organization of ecosystems which then is reflected a range of acceptable outcomes. This will be facilitated by considering multiple scales and dimensions relevant to ecological processes and outcomes and will result in increased flexibility in silvicultural decision making.

Second, an appreciation of the variety of human values, including reflecting those values in research and education, will allow a better understanding of what range of conditions are acceptable. Within this context, accepting and valuing different ways of knowing broadens the base for silvicultural decisions and thus expands the range of management options and public support. This can be accomplished by collaborating with a people with a wide range of values, especially with Indigenous populations and making them a partner in natural resource management. Third, accepting that global change factors are increasingly influencing forest management means that all silvicultural practices will benefit from an acknowledgement of uncertainty. Emphasizing variability, including extreme events, will be crucial to determine what (modifications in) silvicultural treatments will increase the adaptive capacity of the forests.

We understand that such changes in silvicultural activities cannot be viewed in isolation, but require an associated change in other aspects of the forestry sector to be successful. We hope that our proposed definition acts as a push to the broader profession. Just as important, our proposed changes require "capacity building", i.e., providing silviculturists with the proper education and support. This not only includes the aspects about diversity and hierarchical decision making, but also an acceptance of risks and utilization of procedures that allow mistakes to result in learning and improved future silvicultural choices (Walters 1986).

Silviculturists and the whole forestry profession can make a bold statement by updating the definition of silviculture. In the spirit of our proposed definition, it should not be viewed as a doctrine, but as supporting a wide range of management options that accommodate the range of local conditions in ecological, social, and economic settings. Then silvicultural prescriptions can reflect the wide range of values, including reciprocity, respect, biodiversity and economic benefits. Of course, a lot of research (both formal by researchers and informal by practitioners) and educational efforts are needed to allow the new definition to be applied across a broad array of settings. Given our past experience, we are confident silviculturists are up to the challenge.

Acknowledgements The work was supported by the Edmund Hayes Professorship in Silviculture Alternatives at Oregon State University and by the respective institutions of the authors. We would like to thank Maria Janowiak, USDA Forest Service, for her contribution to the early drafts and Christina Eisenberg (OSU) for consultations. Four reviewers and several editors also provided constructive feedback. We dedicate this work to our friends and fellow silviculturists Scott Roberts and Brian Lockhart.

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