Forestry *An International Journal of Forest Research*

Institute of Chartered Foresters

Forestry 2022; **95**, 143–152, https://doi.org/10.1093/forestry/cpab047
Advance Access publication 13 November 2021

The changing culture of silviculture

Alexis Achim[1,†,*], Guillaume Moreau[1,†], Nicholas C. Coops[2,†], Jodi N. Axelson[3], Julie Barrette[4], Steve Bédard[4], Kenneth E. Byrne[2,5], John Caspersen[6], Adam R. Dick[7], Loïc D'Orangeville[8], Guillaume Drolet[4], Bianca N.I. Eskelson[2], Cosmin N. Filipescu[9], Maude Flamand-Hubert[1], Tristan R.H. Goodbody[2], Verena C. Griess[10], Shannon M. Hagerman[2], Kevin Keys[11], Benoit Lafleur[12], Miguel Montoro Girona[12,13], Dave M. Morris[14], Charles A. Nock[15], Bradley D. Pinno[15], Patricia Raymond[4], Vincent Roy[16], Robert Schneider[17], Michel Soucy[18], Bruce Stewart[11], Jean-Daniel Sylvain[4], Anthony R. Taylor[8,19], Evelyne Thiffault[1], Nelson Thiffault[16], Udaya Vepakomma[20] and Joanne C. White[21]

[1]*Centre de recherche sur les matériaux renouvelables, Département des sciences du bois et de la forêt, Pavillon Abitibi-Price, 2405 rue de la Terrasse, Université Laval, Québec, QC G1V 0A6, Canada*
[2]*Department of Forest Resources Management, Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada*
[3]*Office of the Chief Forester - Resource Practices Branch, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, PO Box 9513 Stn Prov Gov, Victoria, BC V8W 9C2, Canada*
[4]*Direction de la recherche forestière, Ministère des Forêts, de la Faune et des Parcs du Québec, 2700 rue Einstein, Québec, QC G1P 3W8, Canada*
[5]*FPInnovations, 2665 East Mall, Vancouver, BC V6T1Z4, Canada*
[6]*Institute of Forestry and Conservation, University of Toronto, 33 Willcocks street, Toronto, ON M5S 3B3, Canada*
[7]*Canadian Forest Service (Canadian Wood Fibre Centre), Natural Resources Canada, 1350 Regent Street, P.O. Box 4000, Fredericton, NB E3B 5P7, Canada*
[8]*Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Drive, Fredericton, NB E3B 5A3, Canada*
[9]*Canadian Forest Service (Canadian Wood Fibre Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada*
[10]*ETH Zürich Institute of Terrestrial Ecosystems, Department of Environmental System Sciences, Universitätstrasse 16, 8092 Zurich, Switzerland*
[11]*Nova Scotia Department of Natural Resources and Renewables, 15 Arlington Place, Suite 7, Truro, NS B2N 0G9, Canada*
[12]*Groupe de recherche en écologie de la MRC-Abitibi (GREMA), Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, 341, rue Principale Nord, Amos, QC, J9T 2L8, Canada*
[13]*Restoration Ecology Research Group, Department of Wildlife, Fish and Environmental Studies, Swedish University of Agricultural Sciences, Skogsmarksgränd, Umeå 907 36, Sweden*
[14]*Ontario Ministry of Natural Resources and Forestry, Centre for Northern Forest Ecosystem Research, 421 James Street South Thunder Bay, ON P7E 2V6, Canada*
[15]*Department of Renewable Resources, University of Alberta, 4-42 Earth Sciences Building, Edmonton, AB T6G 2E3, Canada*
[16]*Canadian Forest Service (Canadian Wood Fibre Centre), Natural Resources Canada, 1055 du PEPS, P.O. Box 10380, Stn. Sainte-Foy, Québec, QC G1V 4C7, Canada*
[17]*Chaire de Recherche sur la Forêt Habitée, Département de Biologie, Chimie et Géographie, Université du Québec à Rimouski, 300 Allée des Ursulines, Rimouski, QC G5L 3A1, Canada*
[18]*École de foresterie, Université de Moncton, campus d'Edmundston. 165 boulevard Hébert, Edmundston, Nouveau-Brunswick E3V 2S8, Canada*
[19]*Canadian Forest Service (Atlantic Forestry Centre), Natural Resources Canada, 1350 Regent Street, PO Box 4000, Fredericton, New Brunswick E3B 5P7, Canada*
[20]*FPInnovations, 570 Saint-Jean Blvd., Pointe-Claire, QC H9R 3J9, Canada*
[21]*Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, V8Z 1M5, BC, Canada*

*Corresponding author: E-mail: Alexis.Achim@sbf.ulaval.ca
†Should be considered as joint first authors

Received 15 February 2021

Changing climates are altering the structural and functional components of forest ecosystems at an unprecedented rate. Simultaneously, we are seeing a diversification of public expectations on the broader sustainable use of forest resources beyond timber production. As a result, the science and art of silviculture needs to adapt to these changing realities. In this piece, we argue that silviculturists are gradually shifting from the application of empirically derived silvicultural scenarios to new sets of approaches, methods and practices, a process that calls for broadening our conception of silviculture as a scientific discipline. We propose a holistic view of silviculture revolving around three key themes: observe, anticipate and adapt. In observe, we present how recent advances in remote sensing now enable silviculturists to observe forest structural, compositional and functional attributes in near-real-time, which in turn facilitates the deployment of efficient, targeted silvicultural measures in practice that are adapted to rapidly changing constraints. In anticipate, we highlight the importance of developing state-of-the-art models designed to take into account the effects of changing environmental conditions on forest growth and dynamics. In adapt, we discuss the need to provide spatially explicit guidance for the implementation of adaptive silvicultural actions that are efficient, cost-effective and socially acceptable. We conclude by presenting key steps towards the development of new tools and practical knowledge that will ensure meeting societal demands in rapidly changing environmental conditions. We classify these actions into three main categories: re-examining existing silvicultural trials to identify key stand attributes associated with the resistance and resilience of forests to multiple stressors, developing technological workflows and infrastructures to allow for continuous forest inventory updating frameworks, and implementing bold, innovative silvicultural trials in consultation with the relevant communities where a range of adaptive silvicultural strategies are tested. In this holistic perspective, silviculture can be defined as the science of observing forest condition and anticipating its development to apply tending and regeneration treatments adapted to a multiplicity of desired outcomes in rapidly changing realities.

Introduction

Silviculture has traditionally been defined as the ‘science and art’ of growing and tending forest crops (Nyland 1996). This refers to both the theory and practice of controlling the establishment and growth of trees to satisfy specific objectives of landowners with forest stands serving as the main unit of intervention. The emergence of silviculture as a discipline dates back to the origins of forest science in Western Europe, with the term having its linguistic roots in ‘care of the forest’. It was introduced in North America much more recently, at the beginning of the twentieth century. Like forest sciences, silviculture did not originate from a desire to harvest trees but from a need to avoid deforestation, promote forest productivity and ensure a continued supply of timber (Puettmann et al. 2012; Gélinas 2010).

Since its origins as a discipline, silviculture has been inherently empirical with a foot in the past, looking to the future. Lifelong growth observations and assessment of consequences of past practices inform current management strategies with the view that these past conditions will accurately reflect future growth potential and stand responses to the local environment. Local climate and soil characteristics are considered permanent features of a site, which determine its potential vegetation and drive its succession dynamics. Accordingly, the majority of silvicultural studies in the scientific literature involve testing the effects of silvicultural treatments on various stand characteristics such as composition (Angers et al. 2005; Webster and Jensen 2007), growth and yield (Roberts and Harrington 2008; Bose et al. 2018; Moreau et al. 2020a), mortality (Caspersen 2006; Thorpe et al. 2008), wood properties (Jaakkola et al. 2005; Peltola et al. 2007) and regeneration (Shields et al. 2007; Poznanovic et al. 2013), each typically considered in isolation of the others. The response is analyzed and interpreted, with consideration to local site characteristics and recommendations prepared on the applicability of the tested approaches for practitioners.

In practice, silviculturists have tended to use such results in conjunction with their own observations and experience to apply sequences of silvicultural interventions, which have been known to produce desirable outcomes in terms of growth, stand composition or wood attributes on a given site. Such scenarios of silvicultural treatments are organized into a limited number of silvicultural systems principally based on regeneration methods and their subsequent impacts on stand structure (Ashton and Kelty 2018). One important drawback of this approach is the standardization of forest practices, which over time can result in the simplification of forest structure and composition, and in turn affect ecosystem functions (Bauhus et al. 2009; Puettmann et al. 2012). Here, we argue that a purely empirical approach to silviculture has become increasingly difficult to justify in the context of unprecedented socio-environmental changes affecting forests worldwide.

First, the process of defining and pursuing silvicultural objectives is inevitably more challenging when multiple stakeholders are taken into account or even involved in forest management decisions (Fürstenau et al. 2007; Puettmann et al. 2015). While the multiplicity of potential objectives has long been recognized (Nyland 1996), expectations of the public on the broader sustainable use of the forest resource beyond timber production are becoming increasingly complex, often leaving silviculturists in the middle of competing expectations (Branca et al. 2020). Second, oversimplification is hardly justifiable given the increasing number of ecosystem services that forests are recognized to perform, which in turn depend on maintaining complexity in forest structures and functions (Puettmann 2011; Messier et al. 2015; Díaz-Yáñez et al. 2020). Third, and most relevant to this paper, the observed shifts in species distributions, the disruption of ecological interactions and the changes in ecosystem productivity induced by climate change (Millar and Stephenson 2015; Trumbore et al. 2015; Zhang et al. 2018) limit the applicability of a fully empirical approach to silviculture. The assumption of a species growing in a stable environmental niche is in many cases no longer valid, and as a result the fundamental premise of the past informing the future is being challenged.

Because of these changing realities, silviculturists are now facing the challenge of prescribing silvicultural treatments to provide the desired suite of ecosystem goods and services that is not only diverse but also evolving continuously over time, on a forested land base being altered at an unprecedented rate. With the traditional tools and approaches of silviculture proving to be insufficient to meet this challenge, the culture of silviculture is changing.

The need for silviculture to recognize the complexity of the forested environment, both in terms of changing environmental conditions and societal demands, has been recognized over the past decade (O'Hara and Ramage 2013; Messier et al. 2015; Hagerman and Pelai 2018). In response, there is a growing body of literature suggesting new principles and approaches of forest management such as managing forest stands for resilience (Mina et al. 2020), adaptive silviculture (Yousefpour et al. 2012), multi-aged management (O'Hara and Ramage 2013) and ecological renovation management (Prober et al. 2019). We suggest that in addition to recognizing the complexity of the changing environment and development of new forest management principles, silviculturists are using new sets of approaches, methods and practices to ensure that silviculture can continue to meet rapidly evolving social demands in equally changing environmental conditions. This process can be described as a change in 'culture' in the sense of this new set of shared approaches, objectives and practices that now characterize the discipline. We argue this change is so profound that it challenges the definition of silviculture as a 'science and art'.

The term 'art' in the traditional definition of silviculture recognizes that silviculturists have to a certain extent relied on a level of intuition or 'gut feeling' in their practice. While recognizing that instincts—often gained through experience—are valuable, we must also consider the limitations of the concept particularly with regards to teaching the next generation of practitioners. Viewing a discipline as a 'science and art' may lead practitioners in training to underestimate the importance of using the most up-to-date scientific knowledge as the foundation of their work. Just as medical surgery was once considered a 'science and art', it is now arguably one of the most advanced scientific professions. A similar transition is occurring in silviculture, which calls for a new definition of the discipline. Silviculture is emerging as an advanced scientific discipline with foundations rooted in our unprecedented capacity to now (1) observe a forest's condition, (2) anticipate its development and (3) apply timely interventions adapted to current and future conditions.

By reviewing the scientific literature, we propose a definition of silviculture as a holistic scientific discipline that relies on many data points or dimensions of measurements throughout the forest lifecycle, allowing it to be highly dynamic and adaptive to rapidly changing social, financial and climatic constraints. At the landscape scale, this concept is referred to as adaptive forest management (Linder 2000; Bolte et al. 2009). Here, we describe a framework that can facilitate its practical implementation at a finer scale i.e. that of forest stands. This conception of silviculture can be framed by three key verbs that we present as pillars of the emergence of silviculture as an advanced science: 'observe, anticipate and adapt' (Figure 1).

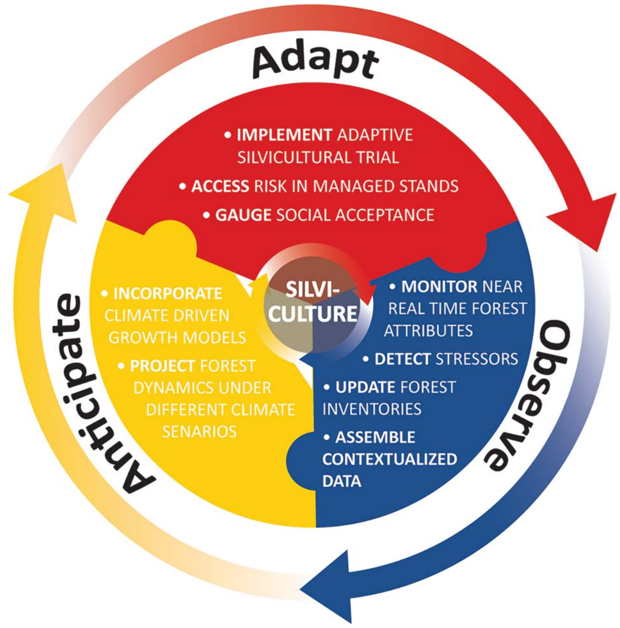

Figure 1 Our conception of silviculture as holistic scientific discipline is framed by three key themes: observe, anticipate and adapt.

Origin and scope of the review

The idea for this review initiates from a workshop on the future of silviculture held in Montreal in March 2019. Researchers and practitioners from across Canada had the chance to exchange on both the realities of current silvicultural practice and the new scientific knowledge and tools needed to adapt to new realities. Although we recognize that our view of silviculture is inevitably influenced by our knowledge of Canadian practices, our literature review was not restricted to any jurisdiction or geographical area. We believe that despite having reached different levels of maturity regionally, the progression of silviculture from an art and science to an advanced scientific discipline is an ongoing process that is occurring around the world.

A wealth of scientific knowledge has been acquired since the emergence of silviculture as a discipline, with significant impact on silvicultural practice. In this review, we focus on the scientific developments that have occurred in the last 10–20 years to provide context about the evolution of the discipline for scientists and practitioners alike. We hope it will be discussed in both communities and stimulate the feedback process between science and practice, which is key to the evolution of any discipline. More specifically, we intend to reach the new generation of students training in forest sciences by demonstrating that silviculture is an exciting, rapidly developing discipline that can offer key solutions to current socio-environmental challenges.

Observe

With the increasing requirement to monitor the growth and development of forest stands, a silvicultural intervention requires accurate, consistent and in many cases spatially explicit information about tree and stand scale attributes before, during and after its application (Mac Dicken 2015). Forest management has long relied on field-based observations of growth and yield including diameter, stocking, height and other inventory standards, which are then statistically extrapolated across the landscape using remote sensing. Quick to adopt the use of aerial photography, both analogue (Aldrich 1953) and more recently digital imagery (Goodbody et al. 2019), silviculturists have long been able to remotely assess stand conditions and develop the appropriate treatment or strategy. However, aerial photographic interpretation is known to often be subjective, time consuming and costly, often with unknown degrees of uncertainty in the estimates (Thompson et al. 2007). The focus on stand rather than tree level descriptions also limits tree-focused silvicultural decisions to be adopted. Similarly, conventional mapping approaches are not well suited to providing information about a broader range of ecological goods and services forests are now recognized to provide, limiting the use of these data to inform non-timber based silvicultural scenarios.

Excitingly, the past decade has seen a revolution in the capacity of silviculturists to observe compositional and functional attributes of trees, forest stands as well as understory vegetation from the ground, air and from space (Almeida et al. 2019). Critical to this increased capacity has been the development and operational use of technologies that allow the 3D structure of vegetation to be accurately quantified using light detection and ranging (LIDAR) technology, an active form of remote sensing that uses pulsed lasers to measure the distance from the sensor to the tree or stand target as well as other digital photogrammetric solutions. LIDAR can be mounted in a variety of platforms, including spaceborne and airborne as well as ground-based instruments. From aircraft both individual tree and 'area-based' LIDAR estimates are providing unprecedented information on the current forest stand structural conditions over large areas (White et al. 2013) and have become an operational technology in many countries tasked with both updating forest inventories as well as developing fine scale digital terrain information to inform forest operations. Ground-based LIDAR systems offer insight into stem dimensions, taper and branching structure (Maas et al. 2008). While less operational than airborne laser scanner, these terrestrial systems are providing very detailed descriptions of stand architecture and individual tree growth dynamics (Côté et al. 2012). Insights into reconstructing canopies using these dense 3D point clouds is also fuelling other approaches such as within canopy photogrammetry-based point clouds (Mulverhill et al. 2020), allowing a 3D structural view of the canopy to be developed more cheaply and quickly. In addition to new sensing technologies, the use of remotely piloted aerial systems (RPAS, also colloquially known as drones) both above and within the canopy are providing new insights into the structure of forest canopies (Coops et al. 2019; Kotivuori et al. 2020). Due to their ease of deployment, RPAS are offering silviculturists the capacity to assess tree and stand structure and composition in near-real time, concurrent with prescription development and implementation (Hyyppä et al. 2020). In the context of rapidly changing growth conditions, the importance of canopy monitoring over time is increasingly important, particularly with stands no longer seen as static in terms of their conditions. Increased sensor development and in-forest connectivity to the internet is allowing near real-time observations of foliage conditions including foliage chlorophyll content and necrosis, which inform early warning systems of stresses such as drought, presence of insects and disease (Culvenor et al. 2014).

Ultimately, innovative silvicultural observation networks provide for the systematic collection of structured data allowing for the development of advanced tools to anticipate change and subsequently adapt silvicultural methods and approaches to meet a large diversity of needs. Near real-time assessments of the forest resource also imply that sequences of silvicultural interventions may be adjusted at any point in time in the forest stand lifecycle, making the reliance on pre-defined silvicultural scenarios less essential. The fundamental changes brought by these new observation tools and techniques to silvicultural practice also ensure data collection and reporting are no longer entirely dependent on sampling theory. Wall-to-wall assessments from remote sensing in conjunction with geo-positioning tools used in forest machinery scheduling allow silvicultural prescriptions to be fine-tuned in space and time. This implies the forest stands represented as uniform polygons on forest maps are no longer a de facto unit of application. Fine-scale, raster-based assessments of forest conditions can help silviculturists fine-tune silvicultural prescriptions according to within-stand variability in forest conditions when necessary (Guay-Picard et al. 2015; St-Jean et al. 2021).

Anticipate

The field observations required for the development of forest growth models cover extended periods of time (Weiskittel et al. 2011). Accordingly, they are generally considered to incorporate the effects of historical climate variation and mortality on growth. However, a recognized limitation of empirical growth models is the underlying assumption that past climate offers insights into future forest stand growth and mortality (Lieffers et al. 2020). This assumption will become progressively weaker in regions where climatic change continues to accelerate (Cox et al. 2000; Wang et al. 2017). Therefore, forest growth models that do not incorporate the effects of short- or long-term climate projections are likely to misrepresent the future. This issue has already been recognized for short-rotation silvicultural scenarios in which the initial environmental conditions can have a major impact on the first few years of stand growth (Almeida et al. 2010).

Incorporating climate drivers into conventional forest growth models is the obvious first step to enable silviculturists to make decisions adapted to future growth conditions. Yearly and monthly climatic metrics such as average temperature and total precipitation are now commonly used in climate-sensitive growth models (Tardif et al. 2001), and have contributed to furthering our understanding of the relationships between tree growth and climate in recent decades (Canham et al. 2018). However, the fact that both the long-term conditions and short-term climatic extremes may alter tree growth suggests there is a need for integrating dendroclimatiological techniques in silviculture. Using such techniques, the annual radial growth of trees can be linked to events occurring at variable severities and time resolutions, i.e. from short, acute events such as storms or droughts to long-term trends of increasing temperatures (Canham et al. 2018; Gazol et al. 2019; Moreau et al. 2020b). This can be achieved using either data mining strategies or prior knowledge of functional links between environmental conditions and tree physiology (Borghetti et al. 2017), although the former option remains limited by the assumption that the effects of past events can be projected into the future.

Process-based physiological models can be used as a complement, so long as a computational structure is provided that predicts forest growth in units that are useful to silviculturists (Mäkelä et al. 2000a). For example, the 3-PG model (physiological principles predicting growth) meets this requirement (Landsberg and Waring 1997) by incorporating simplifications that have emerged from studies conducted over a wide range of forests (Landsberg et al. 2003). Likewise, the PipeQual model utilizes process-based approaches to model tree growth, crown structure and stem form linked to empirical submodels of timber quality (Mäkelä 1997; Mäkelä et al. 2000b). Benefits of these approaches include accommodating variations in the time resolution of events driving tree growth, thereby allowing projections to be made under different future climate scenarios.

Another challenge to the development of climate-sensitive growth projections that are useful to silviculturists arises from the fact that tree growth responses to climatic conditions are mostly inconsistent over time, and abrupt variability is commonly observed following a multitude of physiological processes mostly triggered by stressors such as acute climatic or biotic events (Peltier and Ogle 2020). For example, Anderegg et al. (2015) documented widespread negative legacy effects of a severe drought on tree growth that could outlast the event itself by up to four years, making post-disturbance relationships between growth and climate conditions elusive during such periods. Because climatic disturbances are expected to increase both in frequency and severity with global change (Bell et al. 2004; Gelman 2008; Seneviratne et al. 2012; Zohner et al. 2020), the temporal variability in growth-climate relationships is also expected to increase. This calls for further consideration of the effects of climate at multiple spatial and temporal scales into forest growth modelling efforts destined to assist decision-making in silviculture. To meet this challenge, dynamic global vegetation models (Montané et al. 2017; Koide and Ito 2018; Xia et al. 2019) offer promising new insights that are worth exploring in a silvicultural context (Peltier and Ogle 2020).

Adapt

Climate change is bringing a high level of uncertainty on the long-term response of forests to silvicultural treatments. While general recommendations can be derived from projections of future climate conditions and their anticipated impact on forest dynamics and on the displacement of the bioclimatic range of species (Iverson et al. 2008; Novick et al. 2016), silviculturists will require more targeted information to implement adaptive treatment scenarios. By linking future climate projections to landscape-level assessments of forest dynamics as shaped by disturbance regimes and long-term forest management plans, it is possible to provide spatially explicit guidance for the implementation of cost-effective adaptive silvicultural actions. Such targeted implementation of silvicultural operations and regeneration systems is key to promoting forest landscapes that are both resistant (i.e. the ability to resist change (Millar et al. 2007)) and resilient (i.e. the ability to accommodate change and return to prior condition (Millar et al. 2007)) to rapid changes in environmental conditions, and thus maintaining or even increasing future wood supply as well as other ecosystem services.

Globally, a number of historical silvicultural trials exist, which were designed to examine the growth and establishment of various commercially valuable tree species covering a wide range of environmental conditions. Trees in these plots have in many cases grown, or died, across the forest estate over recent years, thus providing detailed data on how species respond to past climate events or disturbance events. A recent focus of silvicultural science has been to use these existing silvicultural trials in a way that can offer insights into forest management today and into the future (D'Amato et al. 2011; Sohn et al. 2016; Bottero et al. 2017). It is recognized, however, that the analysis of existing trials, albeit in new ways, will be insufficient to provide a comprehensive overview of the responses of key species to current and future conditions (Sohn et al. 2016; Muzika 2017 ; Roberts et al. 2020).

Yet, current forests have all been shaped by their respective histories of past disturbances. Across both climatic and disturbance regimes, studying current forests also provides opportunities to examine which stands have proven to be the most resistant and resilient to disturbance and climatic variation over their lifetime, and which stands have not. By undertaking these retrospective studies, we can examine for specific species how past climatic events such as drought (Sohn et al. 2016), disturbances including insect and pathogens (Muzika 2017; Roberts et al. 2020) and windthrow (Gardiner et al. 2013) have affected tree growth, and quantitatively assess which stand conditions have proven more resistant and resilient. While drivers differ, assessments of stand resistance and resilience can follow similar approaches globally whereby stand structure, composition and growth are examined to derive projections on the growth of future forests and their associated uncertainty or risk of losses (Roessiger et al. 2013; Jactel et al. 2017; Scheller et al. 2018).

Integrating innovative adaptive strategies into silvicultural practices should also be a key area of development for the discipline, with special focus on managing post-disturbance events, specifically harvesting approaches to mitigate the impact of disturbances (D'Amato et al. 2013). With such knowledge acquired through a silvicultural lens, the decision to conduct post-fire salvage harvesting, for example, will be informed not only by the cost–benefit ratio for the primary wood processor (Barrette et al. 2017), but also considering other potential key benefits for the sustainable management of our forests such as regeneration establishment or the economy of forest communities (Thiffault et al. 2013).

The silvicultural community has also implemented networks of assisted migration trials (Isaac-Renton et al. 2014; Nagel et al. 2017), which are among the primary tools envisaged to face the threat of rapid changes in environmental conditions imposed on forests. Yet, there are still relatively few implementations of such trials worldwide. We believe these trials will form the legacy of current silvicultural scientists to future generations. Over time, they will help increase our understanding of the vulnerability of forests to climate change as well as their role as carbon sinks. They will also help identify species and genotypes with higher resistance and resilience to multiple stressors, which in turn will facilitate targeted recommendations for the implementation of assisted migration and colonization in silvicultural practice. Moreover, alongside historical tree improvement provenance tests, such trials will feed genomic analyses of breeding populations

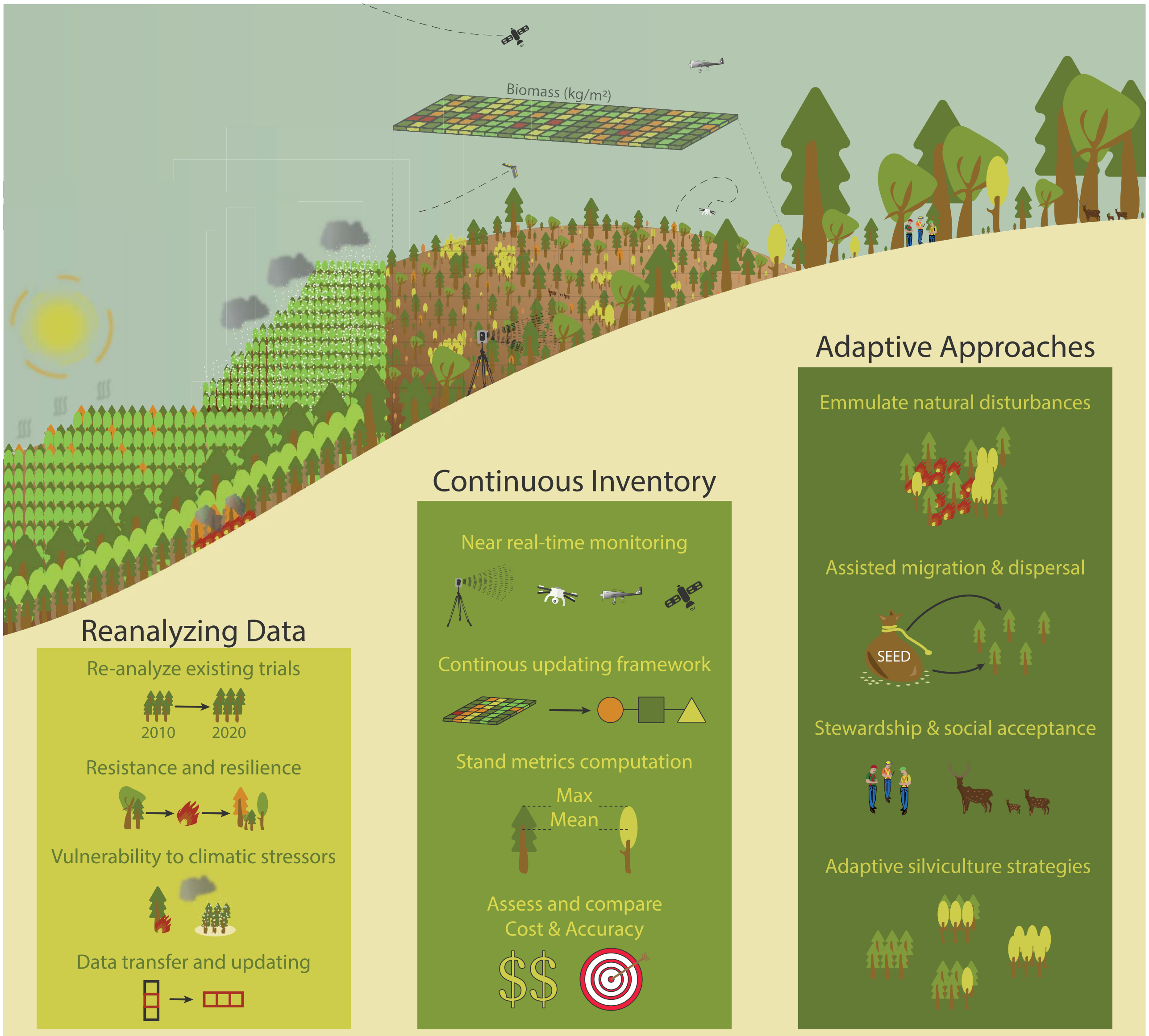

Figure 2 Key steps towards the development of new tools and practical knowledge that will facilitate the implementation of a silviculture designed to meet societal demands in rapidly changing environmental conditions. We categorize these actions into three main groups i.e. reanalyzing data: reanalyzing existing silvicultural trials and databases with a new lens to identify key stand attributes associated with the resistance and resilience of forests to multiple stressors; continuous inventory: developing and mastering new technologies, workflows and infrastructure to provide continuous forest inventories that will guide silvicultural decision-making; adaptive approaches: implementing bold, innovative silvicultural trials in which a range of adaptive silvicultural strategies are tested and their performance compared not only in terms of forest growth and wood supplies, but also of stewardship and social acceptance.

and help provide markers of adaptive traits (Grattapaglia et al. 2009).

Facing unprecedented uncertainties, the science of silviculture needs to offer bold, unusual and potentially risky silvicultural experiments to future generations so they can acquire the knowledge that will allow continuous and timely adaptation. However, the social implications of such innovative silvicultural practices aiming to adapt to future conditions, and more particularly the acceptance of communities to these practices, is only beginning to be understood. Existing research suggests that public, practitioner and stakeholder views are nuanced and contingent. For instance, assisted migration within a species' natural range is largely viewed as an acceptable silvicultural strategy in various jurisdictions across Canada but less so for movement outside of natural range (Peterson St-Laurent et al. 2018, 2021). Furthermore, while publics and stakeholders in forest-dependent communities generally recognize assisted migration as an acceptable strategy, they are skeptical of how decisions about forests are made and by whom (Peterson St-Laurent et al. 2018). Considering the ecological, technological, values-based and governance dimensions of anticipatory and adaptive management protocols, the future of silvicultural research must include the integration of scientific knowledge obtained from diverse forms of expertise (e.g. the natural and social sciences) (Peterson St-Laurent et al. 2020) as well as input from publics, stakeholders, indigenous peoples and local communities.

The way forward

The science of silviculture is adapting to a new reality; the structural and functional attributes of forest ecosystems are being altered significantly in response to a changing climate, and the public demands and expectations on forest ecosystems are becoming increasingly complex, with a broader emphasis on the sustainable use of forest resources beyond timber production. The assumption that the past can continue informing the future, which has been the backbone of silvicultural science, is becoming weaker, and even flawed as climate change continues to accelerate. We suggest that a first step towards the development of new tools and practical knowledge in silviculture should be the re-examination of existing trials and databases (Figure 2a). Building on past efforts, silviculturists need to analyze the results of existing trials with a new lens, to identify key stand attributes that can be linked with the resistance and resilience of forests to disturbances, both anthropogenic and natural (Seidl et al. 2017). Key to this effort will be our ability to link pre-disturbance stand structure and composition to the species- and site-specific vulnerability of trees to multiple stressors and their potential interactions (Jactel et al. 2017). This, in turn, calls for increased interactions between scientists from different communities (Lieffers et al. 2020) who have typically developed their expertise on single forest disturbance phenomena to delve into the confounding effects of multiple disturbances on a variety of long-term forest management goals. For this purpose, the field of silviculture is well placed to lead integration efforts across natural and social sciences, not only as it provides a common set of goals and objectives to the participants, but also offers the tools and intervention capability that are necessary to implement solutions at a large scale.

Second, to inform such an integration effort, national and international efforts should be made to standardize existing field inventory data and tree core protocols into well-documented, broadly applicable and open-access databases to provide observations in formats that facilitate model development and simulations. In parallel, the development of technologies, workflows and infrastructure to allow for continuously updating forest inventory frameworks should be harnessed and implemented at operational scales, moving from static, decadal inventories to near real-time forest observation systems driven by a range of remote sensing data acquired from sensors positioned both within and above forest canopies (Figure 2b). Observations of forest condition used in conjunction with climate-sensitive growth and yield and risk assessment models will enable silviculturists to monitor stresses and disturbances over the entire forest landbase and dynamically adapt any planned sequence of silvicultural interventions in response to both current and projected conditions. In turn, the advent of such capabilities will make the definition of empirically derived sequences of silvicultural treatments less essential.

An important challenge related to this approach is that there is inevitable uncertainty associated with any projected trends in societal or environmental conditions. Such uncertainty can become limiting especially in cases where specific events are identified as drivers of forest condition or growth (Graumlich 1993; Moreau et al. 2020b). Future distributions of exotic pests and disease, or societal demands for wood and/or other forest goods and services are also difficult to anticipate. To meet the challenge of managing forests under such uncertainty, foresters should (1) envisage multiple possible futures by informing their decisions based on projections from different models when available and (2) implement adaptive management by frequently reiterating forest condition, forecasts and objectives (Ogden and Innes 2007; Bernier and Schoene 2009; Gauthier et al. 2014). The 'observe, anticipate and adapt' framework presented in this review could facilitate this process.

Third, there is an imperative need to learn from natural disturbances and understand their key characteristics and how they may be linked to forest resilience, so that they can be emulated in silvicultural interventions (Long 2009). In parallel, there is also a need for bold, innovative silvicultural trials including the implementation of assisted migration, thinning approaches or regeneration methods in which a range of adaptive silvicultural strategies are tested and compared (Figure 2c). With our increased ability to observe forests and monitor change in near real-time, such trials will provide a continuous flow of information to guide ongoing adaptation efforts. Importantly, silvicultural trials can serve as the foundation to acquire and disseminate new knowledge through ecosystem-specific synthesis review and outcomes papers, for example, as well as textbooks for adaptive silvicultural strategies, which are keys to training of the next generation of silviculturists and forest managers worldwide. While implementing these trials, more research should also be conducted in collaboration with social scientists to assess the social context for different forest management regimes including social acceptance of the implemented strategies and practices.

With the clear and present realities of a changing climate and its associated uncertainties, we believe that this holistic conception of silviculture as an advanced observational, anticipative and adaptive discipline is a key to meeting societal demands. This may be seen as an important new step in the evolution of the discipline whereby silviculture can be defined as the science of observing forest condition and anticipating its development to apply tending and regeneration treatments adapted to a multiplicity of desired outcomes in rapidly changing realities.

Acknowledgements

We are grateful to our many colleagues and friends, nationally and internationally who have helped us refine and articulate our thoughts in relation to this piece. In particular, we thank participants at an NSERC-funded workshop on the future of silviculture held in Montreal in March 2019. We would also like to acknowledge the in-kind support of FPInnovations and the Canadian Wood Fibre Centre of Natural Resources Canada (NRCan) in the organization of the workshop. Finally, we would like to thank three anonymous reviewers as well as the Editor-in-Chief of the

journal for suggestions and insights that have significantly improved our paper.

Conflict of interest statement

None declared.

Data availability

No new data were generated or analyzed in support of this research.

Funding

NSERC Alliance project Silva21 NSERC ALLRP 556265–20, grantee Prof. Alexis Achim.

References

Almeida, A.C., Siggins, A., Batista, T.R., Beadle, C., Fonseca, S. and Loos, R. 2010 Mapping the effect of spatial and temporal variation in climate and soils on eucalyptus plantation production with 3-PG, a process-based growth model. *For. Ecol. Manage.* **259**, 1730–1740.

Almeida, D.R.A., Stark, S.C., Chazdon, R., Nelson, B.W., Cesar, R.G., Meli, P. *et al.* 2019 The effectiveness of lidar remote sensing for monitoring forest cover attributes and landscape restoration. *For. Ecol. Manage.* **438**, 34–43.

Aldrich, R.C. 1953 Accuracy of land-use classification and area estimates using aerial photographs. *J. For.* **51**, 12–15.

Anderegg, W.R.L., Schwalm, C., Biondi, F., Camarero, J.J., Koch, G., Litvak, M. *et al.* 2015 Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science* **349**, 528–532.

Angers, V.A., Messier, C., Beaudet, M. and Leduc, A. 2005 Comparing composition and structure in old-growth and harvested (selection and diameter-limit cuts) northern hardwood stands in Quebec. *For. Ecol. Manage.* **217**, 275–293.

Ashton, M.S. and Kelty, M.J. 2018 The practice of silviculture: Applied forest ecology. 10th edn. *Wiley*. 776 pp.

Barrette, J., Thiffault, E., Achim, A., Junginger, M., Pothier, D. and De Grandpré, L. 2017 A financial analysis of the potential of dead trees from the boreal forest of eastern Canada to serve as feedstock for wood pellet export. *Appl. Energy* **198**, 410–425.

Bauhus, J., Puettmann, K. and Messier, C. 2009 Silviculture for old-growth attributes. *For. Ecol. Manage.* **258**, 525–537.

Bell, J.L., Sloan, L.C. and Snyder, M.A. 2004 Regional changes in extreme climatic events: A future climate scenario. *J. Climate* **17**, 81–87.

Bernier, P. and Schoene, D. 2009 Adapting forests and their management to climate change: An overview. *Unasylva* **60**, 5–11.

Bolte, A., Ammer, C., Löf, M., Madsen, P., Nabuurs, G.J., Schall, P. *et al.* 2009 Adaptive forest management in Central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research* **24**, 473–482.

Borghetti, M., Gentilesca, T., Leonardi, S., van Noije, T., Rita, A. and Mencuccini, M. 2017 Long-term temporal relationships between environmental conditions and xylem functional traits: A meta-analysis across a range of woody species along climatic and nitrogen deposition gradients. *Tree Physiol.* **37**, 4–17.

Bose, A.K., Weiskittel, A., Kuehne, C., Wagner, R.G., Turnblom, E. and Burkhart, H.E. 2018 Tree-level growth and survival following commercial thinning of four major softwood species in North America. *For. Ecol. Manage.* **427**, 355–364.

Bottero, A., D'Amato, A.W., Palik, B.J., Bradford, J.B., Fraver, S., Battaglia, M.A. *et al.* 2017 Density-dependent vulnerability of forest ecosystems to drought. *J. Appl. Ecol.* **54**, 1605–1614.

Branca, G., Piredda, I., Scotti, R., Chessa, L., Murgia, I., Ganga, A. *et al.* 2020 Forest protection unifies, silviculture divides: A sociological analysis of local stakeholders' voices after coppicing in the Marganai forest (Sardinia, Italy). *Forests* **11**, 1–22.

Canham, C.D., Murphy, L., Riemann, R., McCullough, R. and Burrill, E. 2018 Local differentiation in tree growth responses to climate. *Ecosphere* **9**, e02368.

Caspersen, J.P. 2006 Elevated mortality of residual trees following single-tree felling in northern hardwood forests. *Can. J. For. Res.* **36**, 1255–1265.

Coops, N.C., Goodbody, T.R. and Cao, L. 2019 Four steps to extend drone use in research. *Nature* **572**, 433–435.

Côté, J.F., Fournier, R.A., Frazer, G.W. and Niemann, O. 2012 A fine-scale architectural model of trees to enhance LiDAR-derived measurements of forest canopy structure. *Agric. For. Meteorol.* **166**, 72–85.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. and Totterdell, I.J. 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**, 184–187.

Culvenor, D.S., Newnham, G.J., Mellor, A., Sims, N.C. and Haywood, A. 2014 Automated in-situ laser scanner for monitoring forest leaf area index. *Sensors.* **14**, 14994–15008.

D'Amato, A.W., Bradford, J.B., Fraver, S. and Palik, B.J. 2011 Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. *For. Ecol. Manage.* **262**, 803–816.

D'Amato, A.W., Bradford, J.B., Fraver, S. and Palik, B.J. 2013 Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecol. Appl.* **23**, 1735–1742.

Díaz-Yáñez, O., Pukkala, T., Packalen, P., Lexer, M.J. and Peltola, H. 2020 Multi-objective forestry increases the production of ecosystem services. *Forestry.* **93**, 84–95.

Fürstenau, C., Badeck, F.W., Lasch, P., Lexer, M.J., Lindner, M., Mohr, P. *et al.* 2007 Multiple-use forest management in consideration of climate change and the interests of stakeholder groups. *Eur. J. For. Res.* **126**, 225–239.

Gardiner, B., Schuck, A., Schelhaas, M.-J., Orazio, C., Blennow, K. and Nicoll, B. 2013 Living with storm damage to forests: What can science tell us. *European Forest Institute.* **3**, 129.

Gauthier, S., Bernier, P., Burton, P.J., Edwards, J., Isaac, K., Isabel, N. *et al.* 2014 Climate change vulnerability and adaptation in the managed Canadian boreal forest. *Environ. Rev.* **22**, 256–285.

Gazol, A., Camarero, J.J., Colangelo, M., de Luis, M., Martínez del Castillo, E. and Serra-Maluquer, X. 2019 Summer drought and spring frost, but not their interaction, constrain European beech and silver fir growth in their southern distribution limits. *Agric. For. Meteorol.* **278**, 107695.

Gélinas, C. 2010 L'enseignement et la recherche en foresterie à l'Université Laval de 1910 à nos jours. 1st edn. *Société d'histoire forestière du Québec* 350 pp.

Gelman, A. 2008 Scaling regression inputs by dividing by two standard deviations. *Stat. Med.* **27**, 4267–4278.

Goodbody, T.R.H., Coops, N.C. and White, J.C. 2019 Digital aerial photogrammetry for updating area-based forest inventories: A review of opportunities, challenges, and future directions. *Curr. For. Reports.* **5**, 55–75.

Grattapaglia, D., Plomion, C., Kirst, M. and Sederoff, R.R. 2009 Genomics of growth traits in forest trees. *Curr. Opin. Plant Biol.* **12**, 148–156.

Graumlich, L.J. 1993 Response of tree growth to climatic variation in the mixed conifer and deciduous forests of the upper Great Lakes region. *Can. J. For. Res.* **23**, 133–143.

Guay-Picard, A., Auty, D., Munson, A.D. and Achim, A. 2015 Partial harvesting in boreal mixedwoods: A case for planned heterogeneity in industrial silvicultural prescriptions. *For. Ecol. Manage.* **358**, 291–302.

Hagerman, S.M. and Pelai, R. 2018 Responding to climate change in forest management: Two decades of recommendations. *Front. Ecol. Environ.* **16**, 579–587.

Hyyppä, E., Kukko, A., Kaijaluoto, R., White, J.C., Wulder, M.A., Pyörälä, J. *et al.* 2020 Accurate derivation of stem curve and volume using backpack mobile laser scanning. *J. Photogramm. Remote Sens.* **161**, 246–262.

Isaac-Renton, M.G., Roberts, D.R., Hamann, A. and Spiecker, H. 2014 Douglas-fir plantations in Europe: A retrospective test of assisted migration to address climate change. *Glob. Chang. Biol.* **20**, 2607–2617.

Iverson, L.R., Prasad, A.M., Matthews, S.N. and Peters, M. 2008 Estimating potential habitat for 134 eastern US tree species under six climate scenarios. *For. Ecol. Manage.* **254**, 390–406.

Jaakkola, T., Mäkinen, H. and Saranpää, P. 2005 Wood density in Norway spruce: Changes with thinning intensity and tree age. *Can. J. For. Res.* **35**, 1767–1778.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B. *et al.* 2017 Tree diversity drives forest stand resistance to natural disturbances. *Curr. For. Reports* **3**, 223–243.

Koide, D. and Ito, A. 2018 Temporal changes in the relationship between tree-ring growth and net primary production in northern Japan: A novel approach to the estimation of seasonal photosynthate allocation to the stem. *Ecol. Res.* **33**, 1275–1287.

Kotivuori, E., Kukkonen, M., Mehtätalo, L., Maltamo, M., Korhonen, L. and Packalen, P. 2020 Forest inventories for small areas using drone imagery without in-situ field measurements. *Remote Sens. Environ.* **237**, 111404.

Landsberg, J.J. and Waring, R.H. 1997 A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.* **95**, 209–228.

Landsberg, J.J., Waring, R.H. and Coops, N.C. 2003 Performance of the forest productivity model 3-PG applied to a wide range of forest types. *For. Ecol. Manage.* **172**, 199–214.

Lieffers, V.J., Pinno, B.D., Beverly, J.L., Thomas, B.R. and Nock, C. 2020 Reforestation policy has constrained options for managing risks on public forests. *Can. J. For. Res.* **50**, 855–861.

Linder, M. 2000 Developing adaptive forest management strategies to cope with climate change. *Tree Physiol.* **20**, 299–307.

Long, J.N. 2009 Emulating natural disturbance regimes as a basis for forest management: A North American view. *For. Ecol. Manage.* **257**, 1868–1873.

Maas, H.G., Bienert, A., Scheller, S. and Keane, E. 2008 Automatic forest inventory parameter determination from terrestrial laser scanner data. *Int. J. Remote Sens.* **29**, 1579–1593.

Mac Dicken, K.G. 2015 Global forest resources assessment 2015: What, why and how? *For. Ecol. Manage.* **352**, 3–8.

Mäkelä, A. 1997 A carbon balance model of growth and self-pruning in trees based on structural relationships. *Forest Science* **43**, 7–24.

Mäkelä, A., Landsberg, J., Ek, A.R., Burk, T.E., Ter-Mikaelian, M., Ågren, G.I. *et al.* 2000a Process-based models for forest ecosystem management: Current state of the art and challenges for practical implementation. *Tree Physiol.* **20**, 289–298.

Mäkelä, A., Sievänen, R., Lindner, M. and Lasch, P. 2000b Application of volume growth and survival graphs in the evaluation of four process-based forest growth models. *Tree Physiol.* **20**, 347–355.

Messier, C., Puettmann, K., Chazdon, R., Andersson, K.P., Angers, V.A., Brotons, L. *et al.* 2015 From management to stewardship: Viewing forests as complex adaptive systems in an uncertain world. *Conserv. Lett.* **8**, 368–377.

Millar, C.I., Stephenson, N.L. and Stephens, S.L. 2007 Climate change and forests of the future: Managing in the face of uncertainty. *Ecol. Appl.* **17**, 2145–2151.

Millar, C.I. and Stephenson, N.L. 2015 Temperate forest health in an era of emerging megadisturbance. *Science* **349**, 823–826.

Mina, M., Messier, C., Duveneck, M., Fortin, M.J. and Aquilué, N. 2020 Network analysis can guide resilience-based management in forest landscapes under global change. *Ecol. Appl.* **31**, e2221.

Montané, F., Fox, A.M., Arellano, A.F., Mac Bean, N., Ross Alexander, M., Dye, A. *et al.* 2017 Evaluating the effect of alternative carbon allocation schemes in a land surface model (CLM4.5) on carbon fluxes, pools, and turnover in temperate forests. *Geosci. Model Dev.* **10**, 3499–3517.

Moreau, G., Auty, D., Pothier, D., Shi, J., Lu, J., Achim, A. *et al.* 2020a Long-term tree and stand growth dynamics after thinning of various intensities in a temperate mixed forest. *For. Ecol. Manage.* **473**, 118311.

Moreau, G., Achim, A. and Pothier, D. 2020b An accumulation of climatic stress events has led to years of reduced growth for sugar maple in southern Quebec. *Canada. Ecosphere* **11**, e03183.

Mulverhill, C., Coops, N.C., Tompalski, P. and Bater, C.W. 2020 Digital terrestrial photogrammetry to enhance field-based forest inventory across stand conditions. *Can. J. Remote Sens.* **0**, 1–18.

Muzika, R.M. 2017 Opportunities for silviculture in management and restoration of forests affected by invasive species. *Biol. Invasions* **19**, 3419–3435.

Nagel, L.M., Palik, B.J., Battaglia, M.A., D'Amato, A.W., Guldin, J.M., Swanston, C.W. *et al.* 2017 Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. *J. For.* **115**, 167–178.

Novick, K.A., Ficklin, D.L., Stoy, P.C., Williams, C.A., Bohrer, G., Oishi, A.C. *et al.* 2016 The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nat. Clim. Chang.* **6**, 1023–1027.

Nyland, R.D. 1996 Silviculture: Concepts and applications. *McGraw-Hill Series in Forest Resources (USA)*. 633 pp.

Ogden, A.E. and Innes, J. 2007 Incorporating climate change adaptation considerations into forest management planning in the boreal forest. *Int. For. Rev.* **9**, 713–733.

O'Hara, K.L. and Ramage, B.S. 2013 Silviculture in an uncertain world: Utilizing multi-aged management systems to integrate disturbance. *Forestry* **86**, 401–410.

Peltier, D.M.P. and Ogle, K. 2020 Tree growth sensitivity to climate is temporally variable. *Ecol. Lett.* **23**, 1561–1572.

Peltola, H., Kilpeläinen, A., Sauvala, K., Räisänen, T. and Ikonen, V.P. 2007 Effects of early thinning regime and tree status on the radial growth and wood density of scots pine. *Silva Fenn.* **41**, 489–505.

Peterson St-Laurent, G., Hagerman, S. and Kozak, R. 2018 What risks matter? Public views about assisted migration and other climate-adaptive reforestation strategies. *Clim. Change* **151**, 573–587.

Peterson St-Laurent, G., Hoberg, G., Sheppard, S.R.J. and Hagerman, S.M. 2020 Designing and evaluating analytic-deliberative engagement processes for natural resources management. *Elem. Sci. Anthr.* **8**, 1–17.

Peterson St-Laurent, G.P., Kozak, R. and Hagerman, S. 2021 Cross-jurisdictional insights from forest practitioners on novel climate-adaptive options for Canada's forests. *Reg. Environ. Change.* **21**, 1–14.

Poznanovic, S.K., Webster, C.R. and Bump, J.K. 2013 Maintaining mid-tolerant tree species with uneven-aged forest management: 9-year results from a novel group-selection experiment. *Forestry.* **86**, 555–567.

Prober, S.M., Doerr, V.A.J., Broadhurst, L.M., Williams, K.J. and Dickson, F. 2019 Shifting the conservation paradigm: A synthesis of options for renovating nature under climate change. *Ecol. Monogr.* **89**, 1–23.

Puettmann, K.J. 2011 Silvicultural challenges and options in the context of global change: “Simple” fixes and opportunities for new management approaches. *J. For.* **109**, 321–331.

Puettmann, K.J., Coates, K.D. and Messier, C.C. 2012 *A Critique of Silviculture: Managing for Complexity*. Island press.

Puettmann, K.J., Wilson, S.M.G., Baker, S.C., Donoso, P.J., Drössler, L., Amente, G. *et al.* 2015 Silvicultural alternatives to conventional even-aged forest management - What limits global adoption? *For. Ecosyst.* **2**, 1–16.

Roessiger, J., Griess, V.C., Härtl, F., Clasen, C. and Knoke, T. 2013 How economic performance of a stand increases due to decreased failure risk associated with the admixing of species. *Ecol. Model.* **255**, 58–69.

Roberts, M., Gilligan, C.A., Kleczkowski, A., Hanley, N., Whalley, A.E. and Healey, J.R. 2020 The effect of forest management options on forest resilience to pathogens. *Front. For. Glob. Chang.* **3**, 7.

Roberts, S.D. and Harrington, C.A. 2008 Individual tree growth response to variable-density thinning in coastal Pacific northwest forests. *For. Ecol. Manage.* **255**, 2771–2781.

Scheller, R.M., Kretchun, A.M., Loudermilk, E.L., Hurteau, M.D., Weisberg, P.J. and Skinner, C. 2018 Interactions among fuel management, species composition, bark beetles, and climate change and the potential effects on forests of the Lake Tahoe basin. *Ecosystems* **21**, 643–656.

Seidl, R., Vigl, F., Rössler, G., Neumann, M. and Rammer, W. 2017 Assessing the resilience of Norway spruce forests through a model-based reanalysis of thinning trials. *For. Ecol. Manage.* **38**, 3–12.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J. *et al.* 2012 Changes in climate extremes and their impacts on the natural physical environment. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 109–230.

Shields, J.M., Webster, C.R. and Nagel, L.M. 2007 Factors influencing tree species diversity and *Betula alleghaniensis* establishment in silvicultural openings. *Forestry.* **80**, 293–307.

Sohn, J.A., Saha, S. and Bauhus, J. 2016 Potential of forest thinning to mitigate drought stress: A meta-analysis. *For. Ecol. Manage.* **380**, 261–273.

St-Jean, É., Meunier, S., Nolet, P., Messier, C. and Achim, A. 2021 Increased levels of harvest may favour sugar maple regeneration over American beech in northern hardwoods. *For. Ecol. Manage.* **499**, 119607. in press.

Tardif, J., Brisson, J. and Bergeron, Y. 2001 Dendroclimatic analysis of Acer saccharum, Fagus grandifolia, and Tsuga canadensis from an old-growth forest, southwestern Quebec. *Can. J. For. Res.* **31**, 1491–1501.

Thiffault, E., Barrette, J. and Paré, D. 2013 Salvage harvesting of fire-killed stands in Northern Quebec: Analysis of bioenergy and ecological potentials and constraints. *J-FOR.* **3**, 16–25.

Thompson, I.D., Maher, S.C., Rouillard, D.P., Fryxell, J.M. and Baker, J.A. 2007 Accuracy of forest inventory mapping: Some implications for boreal forest management. *For. Ecol. Manage.* **252**, 208–221.

Thorpe, A.H.C., Thomas, S.C. and Caspersen, J.P. 2008 Tree mortality following partial harvests is determined by skidding proximity. *Ecol. Appl.* **18**, 1652–1663.

Trumbore, S.E., Brando, P.M. and Hartmann, H. 2015 Boreal forest health and global change. *Science* **349**, 819–822.

Wang, K., Zhang, T., Zhang, X., Clow, G.D., Jafarov, E.E., Overeem, I. *et al.* 2017 Continuously amplified warming in the Alaskan Arctic: Implications for estimating global warming hiatus. *Geophys. Res. Lett.* **44**, 9029–9038.

Webster, C.R. and Jensen, N.R. 2007 A shift in the gap dynamics of *Betula alleghaniensis* in response to single-tree selection. *Can. J. For. Res.* **37**, 682–689.

Weiskittel, A.R., Hann, D.W., Kershaw, J.A. and Vanclay, J.K. 2011 Forest growth and yield modeling. In *Forest Growth and Yield Modeling*. Wiley, p. 418.

White, J.C., Wulder, M.A., Varhola, A., Vastaranta, M., Coops, N.C., Cook, B.D. *et al.* 2013 A best practices guide for generating forest inventory attributes from airborne laser scanning data using an area-based approach. *For. Chron.* **89**, 722–723.

Xia, J., Yuan, W., Lienert, S., Joos, F., Ciais, P., Viovy, N. *et al.* 2019 Global patterns in net primary production allocation regulated by environmental conditions and forest stand age: A model-data comparison. *J. Geophys. Res. Biogeo.* **124**, 2039–2059.

Yousefpour, R., Bredahl Jacobsen, J., Thorsen, B.J., Meilby, H., Hanewinkel, M. and Oehler, K. 2012 A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. *Ann. For. Sci.* **69**, 1–15.

Zhang, T., Niinemets, Ü., Sheffield, J. and Lichstein, J.W. 2018 Shifts in tree functional composition amplify the response of forest biomass to climate. *Nature* **556**, 99–102.

Zohner, C.M., Mo, L., Renner, S.S., Svenning, J.C., Vitasse, Y., Benito, B.M. *et al.* 2020 Late-spring frost risk between 1959 and 2017 decreased in North America but increased in Europe and Asia. *Proc. Natl. Acad. Sci.* **117**, 12192–12200.