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Challenges and opportunities for the operationalization of forest-assisted migration in Canada

Amy Wotherspoon[a], Loïc D'Orangeville[b,c], Nelson Thiffault[d], John H. Pedlar[e], Patricia Raymond[f], Jacob Ravn[b], Melissa Spearing[g], Miriam Isaac-Renton[h,i], Julie Godbout[f], Julie Gravel-Grenier[j], and Donnie McPhee[g]

[a]Department of Forest Resources Management, University of British Columbia, Vancouver, BC, Canada; [b]Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, NB, Canada; [c]Department of Wood and Forest Sciences, Laval University, Québec, QC, Canada; [d]Laurentian Forestry Centre, Canadian Forest Service, Natural Resources Canada, Québec, QC, Canada; [e]Great Lakes Forestry Centre, Canadian Forest Service, Natural Resources Canada, Sault Ste Marie, ON, Canada; [f]Direction de la recherche forestière, Ministère des Ressources naturelles et des Forêts, Québec, QC, Canada; [g]National Tree Seed Centre, Canadian Forest Service, Fredericton, NB, Canada; [h]Department of Forest and Conservation Sciences, University of British Columbia, Vancouver, BC, Canada; [i]Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada, Victoria, BC, Canada; [j]Direction générale de la production de semences et de plants forestiers, Ministère des Ressources naturelles et des Forêts, Québec, QC, Canada

Corresponding author: **Amy Wotherspoon** (email: amy.wotherspoon@ubc.ca)

Abstract

As temperatures increase and suitable forest habitat shift faster than trees can adapt, the impacts of climate change threaten forest health and productivity. Forest-assisted migration (FAM) is a key adaptive forest management tool used to mitigate the effects of climate change by facilitating the movement of tree species or populations to more suitable environments. FAM is guided by climate-based distribution seed transfer models and climate-growth projection models to inform planting stock for reforestation and species conservations. However, large-scale reforestation projects are limited by challenges of the operationalization of FAM. In this synthesis paper, we review these limitations within Canada, including (a) limited provenance trials and data focused on commercial species, often within narrow climate ranges and soil types, (b) lack of infrastructure, storage capacity, and budgets to meet tree seed demand, (c) research and operational practices limited by knowledge transfer and discoverability of data, (d) uncertainties of successful seedling establishment in changing climates, and (e) lack of clear policy guidelines and risk management strategies. We suggest opportunities and a path forward whereby researchers and policy makers can focus efforts to advance FAM towards national-scale operationalization to help meet tree-planting objectives and climate change adaptation goals.

Key words: adaptive silviculture, forest management, forest genetics, species selection, climate change

1. Introduction

Climate change continues to pose a significant threat to forests across the globe via rising temperatures, altered precipitation patterns, extreme weather events, and intensified disturbance regimes (e.g., fire and pests). As temperatures rise and suitable biome habitats shift faster than trees can adapt and/or migrate, disturbances, stressors and competition continue to impact tree growth rates and stand productivity (Gauthier et al. 2015; Brecka et al. 2018). Such impacts threaten forest health and associated ecosystem services, including cultural and spiritual benefits, timber supply, and forest-driven carbon sequestration rates.

Adaptive forest management has been proposed as an approach to help respond to climate change impacts using strategies that promote resistance, resilience, and transition of forested ecosystems (Millar et al. 2007; Nagel et al. 2017). A key tool for meeting adaptive management goals, particularly for transitional silvicultural treatments, is forest-assisted migration (FAM), wherein trees are moved from their home climate to new locations that are projected to experience similar climate in the future—with the goal of maintaining and conserving stand function, productivity, and ecosystem health (Gray et al. 2011; Ste-Marie et al. 2011; Pedlar et al. 2012; Chakraborty et al. 2024). Three types of FAM have been defined (Dumroese et al. 2016), including (1) assisted population migration (moving among seed zones within existing range limits), (2) assisted range expansion (movements at or just beyond existing range limits), and (3) assisted species migration (movements well beyond existing range limits). Climate-based distribution and seed transfer models have recently been used to guide assisted migration of planting stock for reforestation (Gray and Hamann 2013; O'Neill et al. 2017; Van Kerkhof et al. 2022; Royo et al. 2023; Adams et al. 2024) as well as for species conservation (e.g., McLane and Aitken 2012). Simulation experiments project that FAM could increase aboveground biomass, species diversity and sequestration of atmospheric carbon under climate change (Duveneck and Scheller 2015; Hof et al. 2017).

Reforestation, through tree planting operations, provides important opportunities to employ FAM as a climate change adaptation tool. A large-scale example is Natural Resources Canada's 2 Billion Trees (2BT) program, which aims to facilitate the planting of 2BT between 2021 and 2031 to support Canada's 2030 Paris Agreement greenhouse gas reduction targets and contribute towards net-zero greenhouse emissions by 2050 (Environment and Climate Change Canada 2020). Ambitious goals such as these provide opportunities for FAM to act as a natural climate solution implemented at a national level (Mansuy et al. 2022). However, large-scale operationalization of FAM faces multiple obstacles across a variety of stages and scales, including challenges related to individual seedlot collections, plantation establishment, and national policy implementation.

Barriers to FAM have been discussed for the United States (Palik et al. 2022); however, a comparable analysis is needed for Canada given its unique FAM considerations as a northern country with extensive boreal forests and a shared southern border with the United States. Our objective in this paper is to highlight the current challenges and opportunities for FAM as they relate to seed sourcing, species selection and availability in Canada, as well as seedling production and establishment. We focus on FAM in the context of industrial forestry operations and omit discussion of its pros and cons, which have been covered extensively elsewhere (Aubin et al. 2011; Ste-Marie 2014; Argüelles-Moyao and Galicia 2024). Instead, we aim to identify areas of concern and of opportunity whereby researchers and policy makers can focus efforts to advance FAM towards national-scale operationalization, thus helping to help meet tree-planting objectives, biomass targets, carbon sequestration potential, and climate change adaptation goals in Canada.

2. Seed source and species selection

2.1. Seed source selection

Assisted population migration (APM), wherein seed sources are moved within existing species' range limits, is already being implemented in Canada but limited to a few commercial species. Software has been developed to support APM, including climate-matching tools such as the Seedlot Selection Tool (https://seedlotselectiontool.org/sst/) and the SeedWhere web application (https://cfs.cloud.nrcan.gc.ca/seedwhere/). Tools containing genetic information are also available such as the Climate-Smart Restoration Tool (https://climaterestorationtool.org/csrt/) (St.Clair et al. 2022), as well as various provincial-level planning tools (Rainville et al. 2014; Thomas et al. 2024). Many tools are supported by data from provenance trials, which involve the planting (and subsequent monitoring) of range-wide seed sources in series of common garden sites, thus allowing insights into population-level climate responses across species' ranges.

Many Canada-specific tools are becoming increasingly available to support seed transfer decision making. In 2018, British Columbia introduced a climate-based seed transfer system that promotes the northward and upslope movement of seed sources between biogeoclimatic ecological classification units based on critical seed transfer distances (O'Neill et al. 2017). Similarly, in 2020, Ontario introduced a climate-based system that allows seed transfers between ecodistricts with high climatic similarity between historical and near-future time periods (Van Kerkhof et al. 2022). In Quebec, climate-based seed transfer rules have been developed for white (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) BSP) (Rainville et al. 2014). Furthermore, white pine (*Pinus strobus* L.) seed orchards containing both local and southern sources (northern US and Ontario) are being used for the production of seed for planting in southern Quebec (Mottet and Godbout 2020).

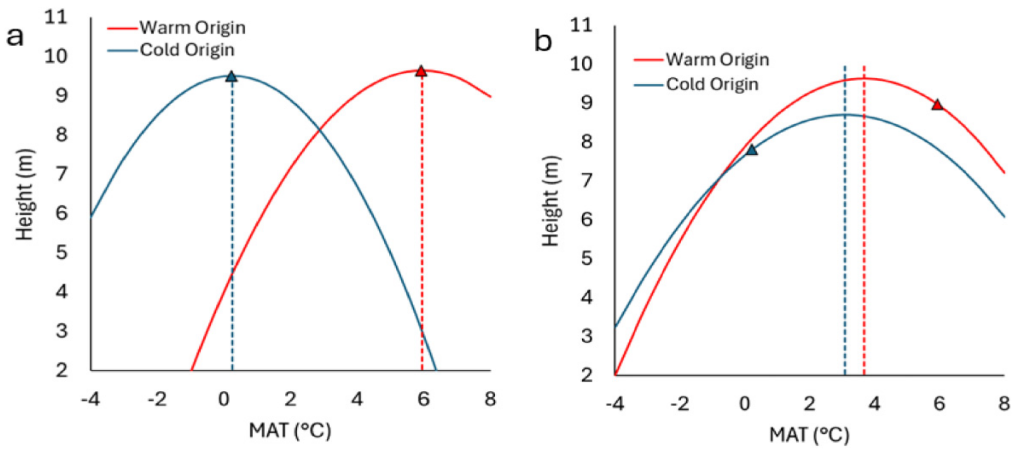
Despite APM moving ahead in several regions of the country, there are a number of challenges to its wider uptake and success. Data from provenance trials are only available for major timber species, which limits the extent to which APM can be incorporated into broader FAM efforts. Even for species with provenance data, trials often sample a narrow climatic range, which may limit insights into population responses to the extreme climate conditions projected under climate change (Benito-Garzón et al. 2013). There are also concerns around the effectiveness of APM as a one-size-fits all solution for climate change adaptation. With strong local adaptation, populations would be expected to have distinct climate response curves, thus offering significant support for APM (Fig. 1*a*). However, northern tree species have been shown to have relatively weak genetic differentiation between populations (Wang et al. 2006; Pedlar and McKenney 2017; Mura et al. 2025), thus within-range population movements may not produce expected levels of climate change resistance (Fig. 1*b*) in the absence of robust data from provenance tests to guide significant transfer distances. Nonetheless, response variables other than height, such as phenology variables (e.g., Mura et al. 2022) may exhibit stronger inter-population differences. However, these remain difficult to assess in large experimental plantations and limited integration into breeding programs.

2.2. Species selection

Species selection may consider various factors, including species' economic values, conservation status, climatic suitability, and life history traits. For example, Curiel-Esparza et al. (2015) employed a decision support system that integrated climate change criteria, such as fire and pest resilience, along with economic and conservation data, to select tree species for reforestation in the southern Spain. Tools exist to support species-level planting decisions in Canada, including trait databases (Boisvert-Marsh et al. 2020) and climatic niche summaries (McKenney et al. 2007; Périé et al. 2014) for a variety of forest plant species.

In the FAM context, species selection decisions apply to both within-range and beyond-range movements. However, given that within-range movements typically focus on population-level selections (as discussed above) and long-distance movements are unlikely to be widely implemented

Fig. 1. Climate response curves for (*a*) theoretical populations exhibiting strong local adaptation and (*b*) 33-year-old black spruce (*Picea mariana* (Mill.) BSP) populations from central Michigan (warm origin, red) and northern Ontario (cold origin, blue) exhibiting modest local adaptation as evidenced by largely overlapping response curves (see Thomson et al. 2009, for further details). Triangles indicate mean annual temperature (MAT) at seed source origin; dashed lines indicate optimal MAT—i.e., temperature at which highest growth rates were achieved.



in the near-term, here we note several unique aspects of species selection in the context of assisted range expansion (ARE). Relatively few examples of ARE exist within industrial forestry, but in 2010 British Columbia adjusted its transfer limits for western larch (*Larix occidentalis* Nutt.), allowing movements beyond existing range limits into several provisional seed transfer zones (Pelai et al. 2021). The limited implementation of ARE likely reflects well-communicated risks associated with extra-range movements, such as the inadvertent creation of invasive species at recipient locations (Ricciardi and Simberloff 2009). Fears of such outcomes are significant barriers to ARE implementation, despite evidence that modest extra-range movements of tree species appear to be relatively low risk (Mueller and Hellmann 2008) and have long been used in forestry operations (Jansen et al. 2017).

There may also be site-related challenges to ARE movements. For example, boreal soil conditions may limit species options at the temperate-boreal forest ecotone (Lafleur et al. 2010), where abiotic (low base cation concentrations) and biotic (mycorrhizal associations) conditions may reduce seedling performance (Carteron et al. 2020). Due to risk of plantation failure, provenance test sites have typically been established within existing species' range limits; thus, older tests may be of limited use for understanding the potential impact of soils (and other abiotic drivers such as daylength) on ARE outcomes.

An opportunity exists to consolidate and assess information from the many historical extra-range tree plantings in Canada and around the world. Such an effort would help to better understand the risks and benefits associated with extra-range plantings, thus addressing a major barrier to ARE efforts. In support of this, there are a growing number of AM trials that incorporate ARE treatments (e.g., Nagel et al. 2017; Royo et al. 2023; Pedlar et al. 2024), which could be used to further inform this topic.

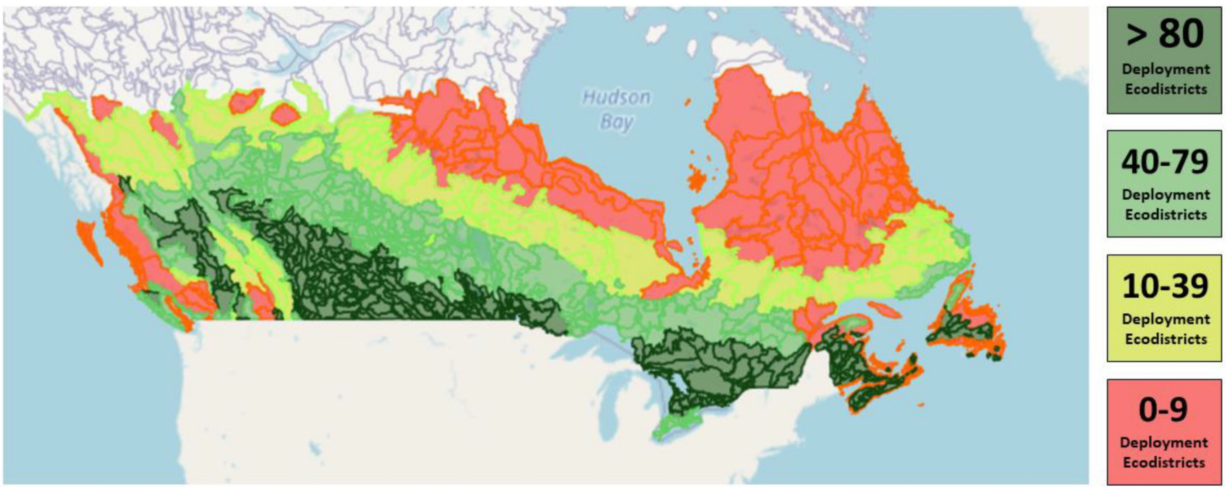
3. Seed availability and seedling production

3.1. Seed availability

The implementation of FAM hinges on the availability of high-quality, genetically representative seedlots from targeted seed procurement zones to maintain or enhance gene flow in advance of climate change (Pedlar et al. 2011; Aitken and Bemmels 2016). In practice, seed sourcing has similar logistical challenges to existing reforestation programs, but needs to expand beyond traditional species and collection zones (Wang and Morgenstern 2009; Dobrowski et al. 2024).

Over the last 125 years, Canadian tree seed collection and deployment systems have evolved in an attempt to address current needs. Tree seed is sourced from wild stand collections, seed production areas, genetic conservation units or reserves and improved seed orchards for both operational and research uses (Thomas et al. 2024). Seed orchards represent the primary source of seed used annually in nursery tree production. However, acquiring FAM seed from existing orchards is often challenging due to limited seed lot representation across species' geographic ranges (Clark et al. 2023; Spearing et al. 2023). One solution could be to establish new seed orchards that feature key FAM material (e.g., southern seed sources); however, such an undertaking would require significant investments of time, energy, and money—all of which are already in short supply at existing seed orchards in Canada. While suitable existing orchards are identified and new orchards are established, wild stand collections remain a valuable alternative for sourcing seeds for FAM, as they are for research and conservation. However, wild collections can be constrained by variable annual seed yields, individual variability (Pérez-Ramos et al. 2014) and costs. Tools to predict when masting events will occur for a given species are needed to improve efficacy of seed collection by collectors who are looking to increase their planning window.

Fig. 2. An example Canada's SeedWhere analysis to assess the ability to deploy domestic tree seed procurement and production areas (e.g., any bulked operational wild stand and untested seed orchard collections from a similar biogeoclimatic zone, represented by ecodistricts) under climate change. The data, from Spearing et al. (2023), consider all future forest-assisted migration seed transfer options whereby a Gower Index was used to measure climate similarity between the average 1961 and 1990 baseline and each of two future scenarios (2011–2040 and 2041–2070) for all combinations of ecodistricts. Three bioclimatic variables were used (mean annual temperature, mean minimum temperature of the coldest month, and growing season length) under the CanESM2 RCP 4.5 emissions scenario using climate data. All current and future seed deployment matches were ranked and retained only if the pair had a Gower metric similarity score of 0.9 or greater (see van Kerkhof et al. 2022 for further discussion of this approach). The figure was created using QGIS, version 3.34 using ecodistrict data from Government of Canada (2017) and climate data from McKenney et al. (2011). Base map from QGIS.org, courtesy of QGIS Geographic Information System.



Predictive modelling for seed collection is currently in development, but more research is needed. Uncertified commercial or mail-order seed sources present an alternative, though they frequently lack detailed information on seed origin and quality, making them unsuitable for use in FAM initiatives. National authorities (typically public agencies and forest geneticists) play a crucial role in ensuring proper certification and traceability of domestically produced, exported and imported tree seeds (Edwards et al. 1988), supported by frameworks such as the Organization for Economic Co-operation and Development Scheme for the Certification of Forest Reproductive Material Moving in International Trade.

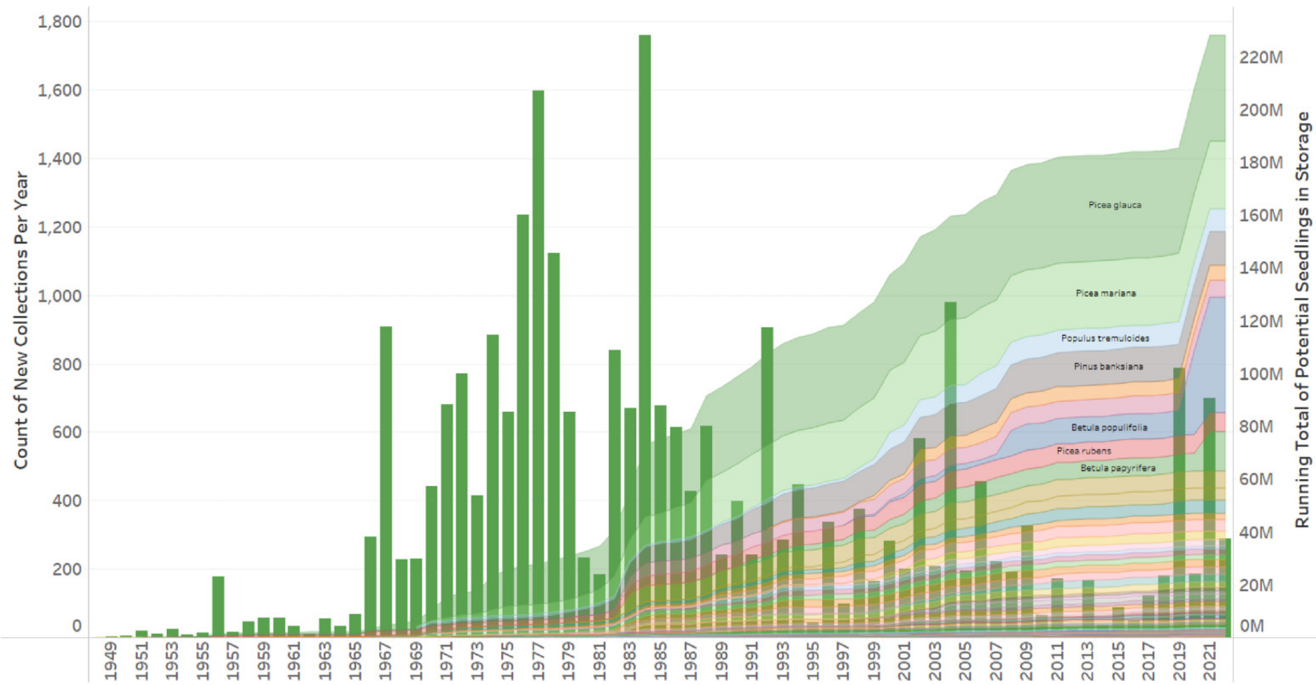
Canadian FAM seed procurement planning is fragmented and lacks a cohesive national strategy, constraining seed supply (Wellstead and Howlett 2017; Cooke et al. 2024). Insight can be gained from action in the US that mandates a comprehensive, multi-agency solution for meeting and sustaining future reforestation and seed supply needs and a federal reforestation target for 2030 (DOI and USDA 2023). There is an opportunity for Canada to achieve this through a virtual seed bank similar to BC's Tree Seed Planning Dashboards for operationalizing seed movements under climate change. Ideally this would be a national initiative with a bottom-up approach whereby different actors from a diversity of provinces would be included in the process and facilitate networking and cross provinces and territory collaboration.

Future efforts to develop a sufficient FAM seed portfolio will need to be guided by a rigorous species-specific gap analysis of existing seed inventory and projected needs. Such efforts will need to account for varying seed collection capacity in target zones, while accounting for potential risks such as drought, wildfire, long-distance shipping, and degrading seed viability (Fargione et al. 2021; Balloffet and Dumroese 2022; DOI and USDA 2023). FAM seeds for northern areas can be generally sourced nationally (Fig. 2), while FAM in southern Canada may require seed sourcing in warmer areas outside the province or country. As climate continues to shift, southern seed sources are expected to become increasingly important, signalling a change in the way that forest seed is managed, with reliance on seed procurement from jurisdictions south of where forest regeneration is occurring. Such cross-border movements can involve challenges, including finding reliable US suppliers, increased costs, and additional phytosanitary requirements (Sáenz-Romero et al. 2020; O'Neill and Gómez-Pineda 2021). In this context, an opportunity may involve establishing seed orchards using southern seed sources, thus ensuring a local supply of key genetic resources under climate change. This could include making use of existing seed orchards in southern Canada and northern United States to obtain planting stock for new installations (via seeds or clones), thus capitalizing on genetic gains and progeny testing associated with existing orchards.

3.2. Seed storage

The maintenance of sustainable, long-term storage of tree seeds is becoming increasingly difficult due to increasing demand, limited collection efforts, and limited specialized infrastructure for seed storage (NASEM 2023; Spearing et al.

Fig. 3. Historical seed collection effort at the National Tree Seed Center (green bars, left), and corresponding potential seedlings available in storage in millions (M), estimated from current or expected viability. Only a few main species are identified. 2020–2023 values may be underestimated due to a lag in seed testing results.



2023). There are currently a dozen ex situ tree seed banks active in Canada but with a limited number of both commercial and non-commercial species. The National Tree Seed Centre (NTSC) hosts the largest diversity of species and seedlots for use by FAM researchers, but still lacks automated FAM decision-making tools to show where seedlots should be deployed. While investing in more seed storage capacity is an obvious solution, locations with surplus storage should be identified (Spearing et al. 2023) along with a seed sharing network to help connect managers to remote resources.

To further complicate matters, desiccation-sensitive (recalcitrant) seeds, such as the oaks (*Quercus* spp.) and walnuts (*Juglans* spp.), are highly sensitive to drying and freezing conditions whereby without adequate moisture, seeds lose their ability to germinate. Because of this, they have a limited operational storage time and—in addition to variable masting cycles—can add considerable logistical hurdles for FAM projects. While we can already identify safe transfer distances for a species like northern red oak (*Quercus rubra* L.) (Pedlar et al. 2024), for example, determining whether these species can be used as seed producers is not yet possible. Even if we know that northern red oak can successfully grow, they may not produce seeds in sufficient quantities and quality to supply FAM programs.

For oak and other species that produce recalcitrant seeds, the use of seed orchards will be mandatory for the operational implementation of assisted migration in eastern Canada. Red oak, for example, requires decades to reach maturity and produces limited seed in its northern range (Gaston 2009). These species exhibit long intervals between planting, short-term species-specific growth maintenance, and the onset of natural regeneration. In such cases, reforestation projects often depend on stored seed reserves (Fig. 3). However, for recalcitrant species, project managers must bet on sufficient tree seed production within a year or two of project initiation. While the NTSC has developed detailed protocols to successfully store many Canadian tree species, additional knowledge is needed to develop storage protocols for novel species, especially recalcitrant species, to minimize seed loss.

Addressing the complexities of operational FAM in Canada requires a strategic approach to the current seed procurement, storage, and deployment systems. By enhancing seed tracking, labelling, and inter-agency coordination, managers, decision-makers, and seed suppliers can address gaps in seed availability and ensure that high-quality seed is accessible for reforestation and adaptation efforts.

3.3. Seedling production

Current tree seedling production in Canada relies on a supply chain of seed sources of known characteristics and origins, with defined seed zones to ensure that seedlings are adapted to local climatic conditions (McKenney et al. 2009). To produce the 625 million tree seedlings used to replant 64% of harvested forest areas annually (698 000 ha; Natural Resources Canada 2023), nursery managers have developed detailed production schedules and protocols for seed stratification, germination, fertilization and maintenance, leading to precise tree sizes and delivery dates to maximize planting success. However, growth targets vary according to species and growing conditions at both the nursery and the planting destination (the Target Plant Concept; see Davis and Pinto

2021). Canadian nurseries are currently under pressure to increase production to satisfy a growing need for seedlings nationally (e.g., to satisfy the needs of the federal 2BT program) and internationally (e.g., 18 million seedlings were exported to the US in 2022; Pike et al. 2023) while also experiencing labour shortages in the field of forestry as a whole (Huq 2007). To satisfy FAM programs, increasing production would also require diversifying species and stock types, a challenge made worse by limited seed availability that involves more handling efforts, as standard equipment is not adapted to low volume and requires manual seeding and transplanting. More importantly, new species incorporated in the production line requires the development of empirical knowledge on its characteristics, including germination success rates, nutrient requirements, growth rates, response to future climate and susceptibility to pests and pathogens.

Increasing production of more diverse species and stock types with limited knowledge and labour shortages needs to be addressed in a context of increasing environmental anomalies that reduce our ability to forecast tree production and our capacity to rely on past production timelines and knowledge. For tree species that have been produced for many years, nurseries manage to adapt and modify their practices according to these changing conditions, while limiting losses. For new species, adapting practices cannot rely on such knowledge, leading to higher uncertainty and seedling losses. Notably, this includes (a) excess precipitation can contribute to the development of root or leaf pathogens (Lilja et al. 2010), (b) exotic and invasive pests and pathogens are increasingly present in tree nurseries and may be introduced from imported seed (Franić et al. 2024), (c) drought episodes lead to seedling water stress, declines in growth, and increased seedling mortality (Lamhamedi et al. 2023), and (d) winter thaws and rapid freezing can lead to frost damage, which can contribute to large seedling mortality. Nurseries often rely on freezer storage of fall-lifted nursery stock to reduce risk of winter damage and early spring warming which often coincide with seed germination. While this is common practice for logistical reasons, nurseries will have to increase their reliance on freezer storage to reduce future risk, which is a major investment and not financially feasible for smaller operations. These ongoing changes can affect the tight production schedule of nurseries. Additional knowledge will be essential to support the production of new tree species for assisted migration, as well as new methods for the rapid identification of diseases to help respond quickly and contain spread within nurseries.

4. Seedling establishment, strategies, and risk management

4.1. Silvicultural foundations for reducing risks to seedling establishment under FAM

Seedling establishment is fundamentally a silvicultural challenge. Under FAM, it requires combining climate-adapted planting stock with site-specific management strategies to support regeneration and promote long-term forest health and productivity. Matching seedling traits to the environmental conditions expected under climate change is anticipated to improve survival and early growth (O'Neill et al. 2017) a strategy consistent with the "target plant concept" (Davis and Pinto 2021). FAM is therefore expected to increase the likelihood of establishment success. However, climate-matching alone may be insufficient as site variability also interacts with compounding challenges from climate extremes and pest or pathogen outbreaks (Allen et al. 2015; Seidl et al. 2017). While these biotic and abiotic factors interact with seedlings' adaptive capacity (Aitken et al. 2008), their impact is further shaped by silvicultural decisions made at stand and landscape scales (D'Amato et al. 2023*a*). Thus, FAM must be approached as part of a broader, adaptive silvicultural framework that can respond to uncertainty. While targeted research is needed to fill critical knowledge gaps (Leech et al. 2011; Nagel et al. 2017; Royo et al. 2023), foresters can apply interim strategies to improve outcomes through microsite selection, vegetation control, or planting density (Park et al. 2014; D'Amato et al. 2023*b*). Regional expertise will be key to tailoring these methods to local conditions.

4.2. Managing transfer uncertainty and maladaptation risk

A key challenge under FAM is the risk of climate mismatches between seedlot and planting site. Seedlings selected for climates too far into the future may not be suited to current conditions and can be vulnerable to frost damage (Benito-Garzón et al. 2013; Bansal et al. 2015; Aitken and Bemmels 2016; Montwé et al. 2018). Risks increase in regions expected to develop no-analog climates, which are combinations of temperature and precipitation with no modern counterpart (Mahony et al. 2017, 2018). These novel conditions require managers to extrapolate seedling responses beyond existing data. Confidence in transfer decisions is further reduced by limited provenance trial data for many species (Etterson et al. 2020; O'Neill and Gómez-Pineda 2021; Benomar et al. 2022). In these cases, patterns of adaptive variation shared among sympatric species can guide transfer decisions, posing fewer risks than the continued use of local seed sources (Aitken and Bemmels 2016). To reduce risk, managers can use a portfolio of seedlots from diverse climatic origins, integrate adaptive silvicultural treatments, or shorten rotation lengths to allow for earlier course correction. Incorporating multiple species or seedlots promotes within-stand genetic diversity, adaptive potential, and productivity (Park et al. 2014; Aitken and Bemmels 2016; Davis and Pinto 2021; Pretzsch 2021).

Uncertainty also arises when little is known about physiological plasticity, or the ability of populations to adjust to environmental change (Champagne et al. 2021; Ravn et al. 2024). However, large-scale field trials such as the Adaptive Silviculture to Climate Change and Desired REgeneration through Assisted Migration projects are beginning to fill key knowledge gaps across Canada and the US (Nagel et al. 2017; Royo et al. 2023; Thiffault et al. 2024). These trials test seed source performance under climate stress. Recent results show that, with appropriate silvicultural systems, southern seedlots can acclimate to novel environments and sometimes outperform local seedlots in traits such as water stress tolerance and photosynthetic efficiency (Dumais et al. 2025). Although evidence supports the acclimation potential of southern seedlots (Ravn et al. 2022), mismatches between seed source and planting environment can nevertheless pose risks during establishment, as the seedling stage is the most vulnerable period in a tree's life (Gray and Hamann 2013). Seedlings are particularly sensitive to stressors such as drought, temperature fluctuations, herbivory, competition, and disease. When environmental conditions differ significantly from the seed source's origin, seedlings may experience reduced physiological function, tissue damage, and elevated mortality (Way and Montgomery 2015; Silvestro et al. 2019; Mura et al. 2022).

To mitigate risks during seedling establishment, conservative climatic transfer distances are often recommended (Ste-Marie 2014; Palik et al. 2022). These involve selecting seedlots for planting sites with climates only modestly different from their source environments. In British Columbia, for example, this approach helps align seedlot selection with both recent climate change and near-future climate trends, typically using 15-year projection windows (Ukrainetz et al. 2011; O'Neill et al. 2017). Conservative transfer distances also help account for non-climatic influences on seedling success, such as soil microbial communities, texture, and nutrient availability (Kranabetter et al. 2015). Transfer guidelines can be further refined by incorporating edaphic variables into species distribution models (MacKenzie and Mahony 2021).

4.3. Silvicultural and genetic strategies for climatic extremes

Another challenge under FAM is the increasing probability of plantations experiencing climatic extremes such as heatwaves and drought (Allen et al. 2015; Philip et al. 2022; Heeter et al. 2023; Zhang et al. 2023), as well as near-term frost events due to temperature fluctuations and transfers into temporarily cooler environments (Benito-Garzón et al. 2013; Bansal et al. 2015; Cohen et al. 2018; Montwé et al. 2018). While FAM is typically guided by average climate projections, managing for extremes is also critical, as tree populations are strongly shaped by selective pressures from cold and aridity (Aitken and Bemmels 2016; Bansal et al. 2016; Montwé et al. 2018; Depardieu et al. 2020; Park and Rodgers 2023).

Several silvicultural strategies can reduce seedling exposure to extreme conditions. For example, systems that retain overstory canopy to buffer seedlings from heat and drought stress using options like underplanting or shelterwood regimes (Park et al. 2014; Royo et al. 2023; Dumais et al. 2025). Site- and microsite-level factors, such as slope and aspect, also influence temperature and moisture conditions and should be incorporated into planting decisions (Henneb et al. 2020). These strategies may be particularly important for shade-tolerant or less drought-tolerant species (Park et al. 2014).

Genetic considerations also form a key part of silvicultural planning under FAM, enhancing resilience to climatic extremes through population selection and breeding. Selecting populations from southern locations or regions with dry summers has been shown to improve drought performance in some species (Bansal et al. 2015; Montwé et al. 2018; Depardieu et al. 2020; Dumais et al. 2025). Where available, genetically-selected seedlots from breeding programs should be prioritized, as these programs target multiple adaptive traits, including size and stress resilience (Moran et al. 2017; Lieffers et al. 2020; Thiffault et al. 2023; Thomas et al. 2024). Seedlots selected for rapid early growth may escape the most vulnerable seedling phase more quickly by improving access to moisture, reducing temperature sensitivity, and enhancing competitive ability (Park et al. 2014). Faster growth may also shorten rotation lengths, allowing for earlier regeneration with seed sources better aligned with evolving climates (Janick 2006; Leech et al. 2011; Park et al. 2014; Serrano-León et al. 2021). Notably, selection for fast growth has not been found to compromise cold hardiness in western Canadian conifers, supporting the use of selectively bred populations in FAM (O'Neill et al. 2014; MacLachlan et al. 2017, 2018; Nuhu 2022).

4.4. Supporting FAM through density and stock-type decisions

Operational adjustments to stand density can help buffer seedlings from climatic stress during early establishment. While high competition can intensify drought stress (Bottero et al. 2016), planting at higher initial densities may increase the likelihood that some individuals survive under uncertain climate conditions. These strategies can improve stocking success by relying on early competition and mortality to favour better-adapted individuals (Stoehr et al. 2010; Pretzsch 2021). Trees remaining after post-establishment thinning or partial cutting often exhibit increased drought resilience (Sohn et al. 2013; Bottero et al. 2016; Bradford et al. 2022; Montwé et al. 2022; McKenzie et al. 2023).

Stock type is another consideration: larger container-grown seedlings can improve root development, water uptake, and resilience to drought (Pinto et al. 2011; Grossnickle and MacDonald 2018; Davis and Pinto 2021; Park et al. 2021). Although higher densities or larger planting stock may entail greater up-front costs, they may reduce establishment failure and downstream intervention requirements.

4.5. Managing for changing competitive dynamics and pest pressures

Competition, pests, pathogens, and browsing all pose significant challenges to forest establishment under FAM (Bower et al. 2024). Forest insects and diseases are becoming more widespread and damaging, threatening productivity, regeneration, and ecosystem services (Allen et al. 2015; Seidl et al. 2017; Kliejunas et al. 2022). Because maladapted seedlings may be more susceptible to these stressors (Aitken et al. 2008), selecting climatically-suitable seedlots is a core FAM strategy to help maintain forest health (O'Neill et al. 2017). However, FAM prescriptions may need to be reinforced by additional silvicultural interventions that address localized biotic pressures.

One such strategy includes silvicultural systems that retain canopy or modify site conditions to buffer seedlings from insect outbreaks by stabilizing microclimate and supporting natural enemies (Park et al. 2014). In high-competition stands, these approaches may also help offset growth limitations associated with underplanting. Genetically-selected seedlots may offer another layer of resilience where breeding programs have incorporated resistance to insect or disease threats (Pretzsch 2021; Thomas et al. 2024). These seedlots may be most appropriate in high-risk zones, but widespread deployment could increase selection pressure on pests (Aitken et al. 2008). Incorporating a diversity of species and seedlots may further reduce pest vulnerability (Aitken and Bemmels 2016) while also enhancing adaptive potential. However, increasing stand diversity may also complicate vegetation management, particularly in controlling invasive species where herbicide applications must accommodate the varying sensitivities of different planted species. Regardless of seed source, controlling vegetation competition remains critical for early seedling survival (Wiensczyk et al. 2011; Davis and Pinto 2021; D'Amato et al. 2023*b*). However, operational trials to inform these practices in the context of FAM remain limited (Royo et al. 2023; Thiffault et al. 2024).

5. The path forward

5.1. Continued research and data collection

Large-scale reforestation initiatives offer opportunities to deploy well-adapted, high-quality seedlings, but supply-chain challenges risk limiting their success. Strengthening collaboration across disciplines can help develop tools and solutions to support both scientific and operational capacity. Research is particularly critical in the Canadian context, where forests span a wide range of climatic gradients and are already experiencing pronounced climate-driven shifts in composition and productivity. Given the scale of these ecosystems and the diversity of values they support, science-based approaches to assisted migration are essential to guide adaptive, resilient management strategies. Adopting advanced technologies and re-purposing existing experiments can provide an opportunity to answer new questions under FAM and climate change extremes (Achim et al. 2022). For example, drone-mounted remote sensors and automated data-processing pipelines could streamline data collection on individual tree response in provenance and progeny trials for faster phenotyping (e.g., D'Odorico et al. 2020). Forest genomic technologies like genomic selection offer new ways to accelerate climate-adapted tree breeding programs (Lenz et al. 2020). While these new phenotyping and genomic tools hold transformative potential, establishing proof-of-concepts for multiple species is critical. This can build public acceptance, attract financial support, and motivate sustained institutional commitments that are key for these long-term forest genetics programs. Operationalizing these methods will also involve developing data quality control and analysis pipelines along with data management systems to process, analyze, and store large volumes of remotely-sensed data.

Utilizing these tools in FAM research provides an opportunity for new partnerships to strengthen innovation while also ensuring that research can meet both immediate operational needs and urgent scientific questions. Working across organizations also allows to pool expertise, facilities and funding, and promote knowledge-transfer outside of open-access peer-reviewed journals. Connecting researchers and land managers through seminars and professional meetings fosters relationships and promotes the exchange of ideas. Reliable core funding is vital as it underpins the ability to secure additional external funding for collaborative projects that explore multidisciplinary questions that would otherwise be beyond the scope of any individual team.

5.2. Developing data pools to refine FAM for climatic extremes

An important opportunity for advancing FAM is the potential for developing a centralized, accessible FAM database that compiles physiological response data across both species and populations. While foundational work exists at both levels (e.g., Morin et al. 2009; Boisvert-Marsh et al. 2020; Pedlar et al. 2021), a dedicated tool could synthesize this dispersed and diverse evidence to better support decision-making. Such a platform could integrate results from field-based common garden experiments and controlled-environment experiments that assess responses to climatic extremes like heat, drought, and shoulder-season frost events. Trait-based experimental data could enhance predictive models by supplying physiological constraints that improve accuracy in novel or extreme climates. To allow integration across studies, the database would need clear trait definitions, consistent terminology, and supporting information on experimental design and measurement protocols.

Such an initiative would require strong institutional support to ensure long-term for data stewardship. For instance, the Canadian Forest Service has developed TreeSource (https://treesource.rncan.gc.ca/en/map), a national database that includes tree measurements, wood quality metrics and some seedlot and phenological data. While not designed specifically for FAM, TreeSource could serve as a foundational architecture. It could be expanded or mirrored to incorporate traits related to climatic stress tolerance, phenology, and physiological plasticity that reflect adaptive thresholds across populations. Such a resource could meaningfully advance the operationalization of FAM by improving predictions of seedling performance, informing transfer distances, and helping managers match planting stock with emerging climatic conditions.

5.3. Continued monitoring

Adaptive management has always been important in land management, but will be crucial to guide FAM and genetic selection programs under ongoing climate change. An iterative process of monitoring progress according to specified objectives and reassessing strategies could support all components of the supply chain—from population testing, to production of seed and seedlings, to site establishment and risk assessment. Planting checks and stocking surveys are well-established tools to evaluate whether stands are on track to meet operational obligations at free-growing and provide opportunities for silvicultural interventions as needed. These

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surveys will become increasingly important to support proactive management in an era of uncertainty, identify species-specific gaps, as well as potentially update growth and yield models, which help establish sustainable harvest rates.

Given the rapid pace of climate change, maintaining nimbleness will be key to meet current indicators of success, defined in stocking standards. These guidelines specify the density, composition, and properties of trees required to restore a harvested stand to a desired forested state. Flexibility may be necessary if standards evolve as new information and practices emerge under FAM and increasingly challenging conditions. The goal remains establishing seedlings that survive and thrive to regenerate healthy, productive forests.

5.4. Economic evaluations

While some silvicultural approaches may enhance seedling establishment under FAM, there may be financial barriers impeding implementation. Researching how FAM contributes to financial gains under various management options will help optimize returns on investment. Economic evaluations could focus on shorter-term effects of survival and need for subsequent interventions, as well as longer-term impacts like product quality (e.g., Chagnon et al. 2024). Diversifying Canada's forest economy through the use of climatically suitable, genetically selected seedlots can help meet emerging market demands while supporting a competitive forest industry.

5.5. Continuing to build trust and inform policy

The climate-based seed transfer programs that are moving forward within Canada have been built on strong government-industry forest policy collaborations. While relatively high levels of public support for FAM exist in British Columbia, Alberta, and Quebec (Hajjar and Kozak 2015; Moreira et al. 2024) persistent concerns remain relating to forest governance and trust (Peterson St-Laurent et al. 2018). As has been demonstrated in the context of BC, these scientific and political collaborations have tended to generate knowledge for use by the forest sector and government scientists with backgrounds limited to biophysical disciplines, such as genetics (Hagerman and Pelai 2018; Pelai et al. 2021). Similar instances have occurred worldwide (Forsyth and Walker 2008), resulting in narrowing viewpoints that can be malignant to knowledge formation. In these instances, knowledge production from limited perspectives becomes a tool of social (and epistemic) exclusion by rejecting specific ways of knowing and leaving out many other considerations and dimensions.

Collectively, this narrowed viewpoint of knowledge creation is described by the knowledge co-production model referring to the observation that institutions of knowledge and of decision making are mirrors of each other (Jasanoff 2004). Put differently, this explains how the scientific practices—and what counts as credible, legitimate, and salient evidence relevant for decision making—both reflect and reproduce existing relations of power (Jasanoff 2004; Turnhout 2024). Viewed through this lens, we see how knowledge regimes and limited understanding build up around a given issue (Hagerman et al. 2021), including the large-scale operationalization of FAM and meeting large-scale climate adaptation targets. This can create problems on many levels as indicated above, including the fact that challenges associated with implementing FAM, like most other environmental challenges are inextricably social, ecological, and technical. Thus, ensuring a comprehensive diagnosis of the challenge and meaningful, just and transformative solutions, requires a range of diverse perspectives and worldviews be brought to bear.

Effective implementation of FAM requires recognizing that systems of science and decision-making are interconnected and often resistant to change. Calls and claims for the need and importance of multiple knowledge systems in resource management and environmental decision making are commonplace and have been with us for decades (e.g., Pouliot and Godbout 2014). To tackle the logistical complexities of FAM in a changing climate, stakeholder and rights-holder engagement, community-engaged and Indigenous research and efforts towards the democratization and decolonization of knowledge are widely recognized as essential (Hewlett 2002; Dietz and Stern 2008; Peterson St-Laurent et al. 2018). Individually, these processes are important and necessary, but insufficient. Instead, the invitation put forward here is for institutions, initiative and/or collaborative research initiatives to first increase awareness and reflection about the types of knowledge considered to be credible and valid, particularly when determining species selection, planting strategies, and risk management. Secondly, to remain intentional and deliberate with action towards ensuring the governance structures, institutional rules and processes are in place to meaningfully support diverse perspectives that can be applied to addressing the complex environmental challenges and improving policy and practice of FAM. For example, this might include recognizing and incorporating multiple types of social science perspectives such as economics, shifts in norms, ethics, behaviour change, politics and power (as well as their cause) and knowledge generated within different worldviews (such as traditional ecological knowledge) and at multiple scales. Doing so is essential for making meaningful progress towards FAM planning, research, and management and to effectively address complex climate challenges, enhance public trust, and increase the likelihood of long-term success of operationalizing FAM within Canada and the US.

In memoriam

We dedicate this work to the memory of Melissa Spearing, our esteemed colleague and co-author, who sadly passed away during the writing of this manuscript. Melissa was a dedicated professional whose passion for seed biology and commitment to advancing knowledge had a profound impact in the field of forestry and the wider scientific community. Her insightful contributions to this manuscript, as well as her broader body of work, will continue to inspire future research. Her legacy will live on in the important work she has left behind.

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Author information

Author ORCIDs

Amy Wotherspoon https://orcid.org/0000-0001-6480-2318
Nelson Thiffault https://orcid.org/0000-0003-2017-6890
Patricia Raymond https://orcid.org/0000-0002-1835-5139
Jacob Ravn https://orcid.org/0000-0001-6015-2098

Author notes

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Author contributions

Conceptualization: AW, LD, NT
Funding acquisition: LD
Investigation: AW, LD, NT, JHP, PR, JR, MS, MI, JG, JG-G, DM
Project administration: AW
Supervision: AW, LD, NT
Visualization: AW
Writing – original draft: AW, LD, NT, JHP, PR, JR, MS, MI, JG, JG-G, DM
Writing – review & editing: AW, LD, NT, JHP, PR, MI, JG, JG-G, DM

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