The implementation of assisted migration in Canadian forests

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ABSTRACT

We outline the major steps involved in implementing assisted migration (AM) and assess, in a general way, the capacity to carry out each step in Canadian forests. Our findings highlight the fact that capacity to implement AM differs between forest species; in particular, the existence of established provenance trials, seed transfer guidelines, seed procurement systems, and plantation establishment protocols makes AM considerably more feasible for most commercial tree species than for most species of conservation concern. We report on several AM efforts involving commercial tree species that are already underway in Canada and identify a number of initiatives that could be undertaken to help build AM capacity. This paper is not intended as an endorsement of the AM approach; however, we feel there is considerable value in discussing implementation issues at this point in the AM debate.

Key words: assisted migration, implementation, provenance data, seed procurement, Canada, forest, seed transfer, climate change

RÉSUMÉ

Les auteurs donnent un aperçu des principales étapes de la mise en œuvre de la migration assistée (MA) et évaluent, de manière générale, la capacité d'exécuter chacune des étapes dans le contexte des forêts canadiennes. Les conclusions indiquent que la capacité de mise en œuvre de la MA varie selon l'essence forestière; plus particulièrement que l'existence des tests de provenance, les lignes directrices concernant le transfert des semences, les systèmes d'acquisition de semences et les protocoles d'établissement de plantations facilitent considérablement plus la MA des essences commerciales, comparativement aux essences préoccupantes sur le plan de la conservation. Les auteurs décrivent plusieurs exemples de MA d'essences commerciales au Canada et présentent certaines initiatives qui permettraient d'accroître la capacité en matière de MA. Ce document ne vise pas à prôner la MA, cependant les auteurs sont de l'avis qu'il y a avantage à discuter des questions de mise en œuvre à cette étape du débat sur la MA.

Mots clés : migration assistée, mise en œuvre, données de tests de provenance, acquisition des semences, Canada, forêt, transfert des semences, changements climatiques

Introduction

The term “implementation” denotes a move from the conceptual to the practical—a shift from theory to action. Reporting on assisted migration (AM) implementation may seem premature given the substantial uncertainty around spatiotemporal patterns of climate change, the well-documented risks associated with AM (Schwartz 2005, McLachlan *et al.* 2007, Ricciardi and Simberloff 2009), and the relative infancy of the science and public debate on the topic; however, some Canadian agencies have already modified seed zone policy and practice in response to climate change. In addressing this topic, our intent is not to advocate a “full steam ahead” approach to AM, but to report on the state of the resources (i.e., knowledge, tools, data, and practices) needed to carry

out sound, science-based AM initiatives—if and when such initiatives are deemed appropriate. Despite our focus on the practicalities of AM, we acknowledge that complex decisions pervade any implementation of AM and present profound challenges to existing conservation and management frameworks.

Contemporary forest management is organized according to a variety of objectives ranging from intensive cultivation of timber to the protection of endangered species. Different types of AM can be discerned along this spectrum (Ste-Marie *et al.* 2011). For example, AM involving commercial tree species would often make use of existing seed transfer data, seed procurement networks, and established practices around plantation establishment and management in order to estab-

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lish seed sources (also referred to as genetic material, seedlots or populations) at sites with projected suitable future climate. Due to the often extensive geographic range of these species, this type of AM would typically focus on seed movements within, or modestly beyond, a species' current range. For species of conservation concern, this base of knowledge and experience is often lacking; thus, AM initiatives involving these species would likely be guided by simple climate matching and involve a substantial investment in developing best practices around seed collection and plantation establishment. Since these species often have limited geographic ranges, this type of AM would necessarily involve seed movements outside the species' current distribution. Throughout this paper, we discuss AM implementation both in the context of commercial tree species and forest plant species of conservation concern.

Climate projections vary widely across different general circulation models (GCMs) and emissions scenarios (IPCC 2007). This uncertainty presents a major challenge to climate change adaptation efforts (Lemos and Rood 2010). For AM implementation, it means that forest managers cannot be sure of the rate and trajectory of climate change at both the seed source and planting site—key information in any AM initiative. Furthermore, even if the spatiotemporal patterns of climate change could be accurately predicted, the response of vegetation to those changes is often not clear. Below, we present several options that can be used to address climatic uncertainty during seed source selection and planting, but we acknowledge that the issue of uncertainty remains challenging for many aspects of AM implementation.

Here we report on the state of assisted migration tools and techniques to mitigate climate change impacts on forest species in Canada. The paper explores important issues that a forest manager will need to address in order to implement an AM project, including selecting an appropriate species; calculating a suitable migration distance; obtaining seed from selected sources; identifying a suitable planting site; and undertaking effective planting, tending, and monitoring. We also briefly discuss the financial implications of AM and summarize active AM initiatives in Canada. Finally, we identify a number of initiatives that could be undertaken to help build AM capacity. We suggest that this is a critical time to take stock of Canada's capacity to engage in AM given the recent groundswell of interest in the topic (Hewitt *et al.* 2011), the emergence of several AM initiatives in Canada, and ongoing evidence of rapid climate change (WMO 2010).

Selecting Species

For commercial tree species, which are often abundant and widespread, AM efforts would target species projected to show substantial declines in productivity under climate change (O'Neill *et al.* 2008b). The extent to which growth will decline depends in large part on the degree of local adaptation, with higher degrees of local adaptation risking steeper growth declines (Aitken *et al.* 2008). Range-wide provenance data can be used to calculate the degree of local adaptation to climate and, consequently, some of the expected impacts of climate change on a species' growth. Further details on the use of provenance data in implementing AM are outlined below.

For species of conservation concern, several life history characteristics have been proposed as indicators of AM suit-

ability, including rare, threatened or endangered status; niche width; degree of habitat specialization; and migration potential (Hunter 2007, Keel 2007, Vitt *et al.* 2010). These characteristics could be used in combination with results from climate envelope studies (e.g., McKenney *et al.* 2011) to further prioritize species with respect to potential climate change impacts (Vitt *et al.* 2010). The review of existing species vulnerability assessment tools is the subject of another paper in this issue (Beardmore and Winder 2011).

A major concern when choosing a species for AM is that it may negatively impact existing populations at the new location. Problems could take the form of an invasive expansion by the transferred species, genetic contamination of species at the transplant site through hybridization with the transferred species, or through diseases and parasites introduced to the recipient location (Ricciardi and Simberloff 2009). Numerous studies have attempted to profile successful invaders (e.g., Baker 1965), but ultimately with limited success (Perrins *et al.* 1993, Williamson 1999); factors such as rapid evolutionary change by invaders upon arrival in the new location, chance long-distance dispersal events, and long lag periods before invasions take-off make it difficult to predict the invasiveness of a species *a priori* (Richardson and Pyšek 2006).

In fact, the concept of "invasive" species becomes problematic in a world where species are, to varying degrees, naturally shifting their ranges and relative abundances. If the goal of AM is to shift the native range of species to new locales and to restrain their impact within narrow production or conservation parameters, then we will likely often fail. We must acknowledge that introducing species into novel climates may have profound biotic impact (Aubin *et al.* 2011).

Migration Distance

Central to AM is the relocation of regenerative material (henceforth "seeds" or "seed source") to sites that are projected to be climatically favourable at some point in the future. In the northern hemisphere, this generally implies planting seed at sites that are north of, or at a higher elevation than, the seed's natural geographic origin (or provenance). Alternatively, from the perspective of the plantation, it means procuring seed from locations that are south of, or at a lower elevation, than the proposed plantation site.

The choice of a suitable migration distance has implications for the success of an AM effort; moving seed too far may result in low seedling survival, while not moving it far enough may fail to mitigate future climate change impacts. The geographic (or climatic) distance that seed should be migrated to optimize plantation health and productivity over the rotation has not been carefully examined. The following section presents several approaches that have been proposed to help determine appropriate seed migration distance.

Using past and projected climate change to calculate migration distance

In the absence of provenance data (detailed below), finding a match between current climate at the seed source and projected future climate at the planting site may be the best approach for determining an appropriate seed migration distance. For example, if seed is available from a location that currently experiences a mean annual temperature (MAT) of 4°C, then locations projected to experience MAT similar to

4°C in the future would be candidate deployment sites for that seed source. Alternatively, for an available planting site that is projected to experience MAT of 4°C in the future, seed sources currently growing at MAT of 4°C would constitute candidate seed procurement sites.

This approach requires the identification of a future point in time which, in turn, determines the future climate value to be matched (and consequently the distance that seed is transferred). For commercial tree species, it has been proposed that targeting the climate anticipated at one-third of the rotation length (e.g., at approximately 25 years from present for 75-year rotations) may achieve a balance of adaptation over the rotation by favouring adaptation during plantation establishment when trees are most sensitive to stress (Ukrainetz *et al.* 2011). For other plant species, which lack the fixed harvest schedules and growth-oriented management objectives of forest plantations, this issue remains unresolved.

Climate change in the recent past should also be considered when calculating an appropriate AM distance (McKenney *et al.* 2009). Evolving and migrating slowly, tree populations today are likely locally adapted to climates prevalent when they, or their recent ancestors, were established, perhaps 100 to 300 years ago. Thus, some long-lived forest trees may already be growing under suboptimal climate conditions—a situation that could be addressed, along with projected future climate changes, when moving seed sources. For example, at the turn of the century, MAT in southern Canada was about 1°C cooler than contemporary climate (Zhang *et al.* 2000). Furthermore, a change in MAT of about 1°C is projected for Canada over the next 25 years (Lemprière *et al.* 2008). Thus, if incorporating both past and future climate change, seed would be migrated to planting sites that have a current MAT about 2°C cooler than current MAT at the seed source.

Advances in the field of tree epigenetics indicate that the temperature at which seeds develop influences cold hardiness and bud phenology traits in resulting progeny (Johnsen *et al.* 2005, Yakovlev *et al.* 2011). This phenomenon may reduce the need to include past climate change when calculating migration distance, since seeds/seedlings will, to some extent, be “tuned” to the temperature experienced by the maternal parent at the time of seed development. Though this effect may shorten assisted migration distances and speed the process of forests adapting to new climate conditions, there are still many unknowns concerning its magnitude, duration, and pervasiveness across forest plant species (Aitken *et al.* 2008).

Once a migration distance has been determined, potential seed procurement/deployment areas can be identified on maps (or grids) of current/future climate—a relatively straightforward GIS procedure, but one still complicated by the uncertainty in timing and extent of climate change. Of course, MAT is not the only climate variable driving patterns of population differentiation, nor is it the only climate variable that has changed and continues to change. Seed migration distance should therefore be determined by overlapping potential seed procurement/deployment areas, each associated with a single climate variable. Climate variables used in this procedure should be adaptively significant (i.e., have impacts on traits related to population survival and growth) and weakly correlated with each other (e.g., MAT and annual precipitation; Andalo *et al.* 2005).

Seedwhere (McKenney *et al.* 1999) is an example of a computer program that matches seed source to planting site under both current and future conditions. The program calculates a climatic similarity index between a target location (i.e., seed source or planting site) and each location across a study area using a modified Gower metric (Gower 1971). The metric expresses the difference in climate between any two locations as a proportion of the difference in climate across the entire study area. One advantage of the *Seedwhere* approach is that the index can be generated using any number of climate variables with the final index value computed as an average of the Gower metric for each climate variable. Fig. 1 shows the results of a *Seedwhere* analysis that identifies suitable seed procurement (Fig. 1a) and deployment (Fig. 1b) areas for North Bay, Ontario.

Critical Seed Transfer Distance

Critical seed transfer distance is the maximum geographic, climatic, or adaptive genetic distance seed can be transferred and still maintain acceptable levels of growth and adaptation (Ukrainetz *et al.* 2011). A critical seed transfer distance (in climate units) can be applied to either side of a seed source or plantation climate to identify a seed deployment or procurement area, respectively. When AM is utilized, the critical seed transfer distance is applied to either side of a target seed source climate (calculated as seed source climate minus migration distance) or target plantation climate (calculated as current plantation climate plus migration distance) to identify a migrated seed deployment or procurement area, respectively.

For commercial tree species in some jurisdictions, data from provenance trials may be available to calculate critical seed transfer distance (Raymond and Lindgren 1990). Provenance tests generally consist of plantings of populations from a wide range of locations (i.e., provenances) at a number of test sites (or common gardens; see Morgenstern 1996 for full description and history). Performance characteristics (e.g., survival, height, DBH) of each population at each test site are then measured periodically. From these data, transfer functions can be developed that relate the performance of various provenances at a given test site to the climatic distance between the provenance and test site. Data from several test sites are often pooled, in which case response variables are expressed as a percentage of the local population or expected performance of a local population (Schmidtling 1994, Carter 1996).

Transfer functions have been used to guide seed movement under climate change (Andalo *et al.* 2005, Beaulieu and Rainville 2005, O'Neill *et al.* 2008a, Thomson and Parker 2008, Thomson *et al.* 2009, Ukrainetz *et al.* 2011). Fig. 2a shows a pooled transfer function for a hypothetical species; vertical lines indicate the critical seed transfer range. In the absence of climate change, seed could be deployed to, or procured from, locations that differ in MAT by up to $\pm 2^\circ\text{C}$ (the critical seed transfer distance) from the plantation or seed source respectively, without incurring excessive growth loss (Fig. 2b). To incorporate assisted migration, the critical seed transfer distance is applied to either side of the target seed source or plantation climate to identify the migrated seed procurement (Fig. 2c) or deployment (Fig. 2d) area.

Clearly, the availability of provenance data presents a wide range of options for guiding seed movements in an AM pro-

Fig. 1. Results of a *Seedwhere* (McKenney *et al.* 1999) analysis, showing: **(A)** climatic similarity between the future climate (i.e., 2041–2070) for North Bay, Ontario (shown as a white dot) and the current climate (i.e., 1971–2000) at each grid cell across the study area, and **(B)** climatic similarity between the current climate (1971–2000) for North Bay, Ontario and the future climate (2041–2070) at each grid cell across the study area. Warmer colours indicate a closer climate match. The analysis employed two climate variables (i.e., mean annual temperature and annual precipitation); future projections were based on CGCM3.1 (McFarlane *et al.* 2005) and the A2 emissions scenario (Nakicenovic and Swart 2000).

gram. While there has been a substantial amount of provenance data gathered in Canada over the past century, much of these data are unpublished or difficult to access. Given the central role of provenance trials for AM efforts, the development of an extensive, centralized, and widely available database of Canadian provenance data would be useful. Such an effort could be coordinated with comparable efforts that are ongoing in the United States (The Center for Forest Provenance Data⁶).

⁶<http://cenfor.gen.forestry.oregonstate.edu/index.php>

Incorporating Uncertainty into Seed Transfer Decisions

The methods discussed above provide highly specific instructions for AM-based seed movements, but do little to address the uncertainty around the timing and magnitude of regional climate change (Knutti 2008). Rehfeldt and Jaquish (2010) addressed this challenge by generating migrated seed deployment zones for a given seed source for two climate scenarios for each of three GCMs. The zones were then overlaid and areas where multiple zones overlap were identified as suitable for deployment across multiple future climates. Alternatively, uncertainty could be addressed by planting a site with multiple seed sources each from a slightly different climate. For

Fig. 2. Hypothetical example illustrating: **(A)** a pooled transfer function with vertical lines indicating the deployment limits within which acceptable levels of growth are maintained; **(B)** the seed deployment/procurement area for Sudbury, Ontario (shown as a black dot) based on this transfer function; **(C)** the migrated seed procurement area for Sudbury; and **(D)** the migrated seed deployment area for Sudbury. The migrated deployment /procurement areas are based on climate projections from CGCM3.1 (McFarlane et al. 2005) and the A2 emissions scenario (Nakicenovic and Swart 2000) for the 2041–2070 period.

example, multiple seed sources could be identified for a given planting site by generating separate seed procurement zones for a number of plausible future climate paths (i.e., GCMs and emission scenarios). Seed from each of the identified procurement zones could then be planted at the target location.

Crowe and Parker (2008) formalized this approach by applying the principles of modern portfolio theory to identify a set of provenances that minimize risk and maximize adaptive suitability at a planting site. They demonstrated their approach using a focal point seed zone model (Parker 1992, Parker and van Neijenhuis 1996), which estimated the adaptive suitability of white spruce (*Picea glauca* [Moench] Voss) in relation to a location in northern Ontario for each of five GCM/emission scenario combinations. The outputs from this model were submitted to a portfolio model that minimized the risk (i.e., the variance and covariance) associated with selected seed sources given a minimum rate of return (i.e., adaptive suitability). Seed sources selected using this method were well spread geographically across the province and var-

ied widely in their projected suitability across GCMs and scenarios—a result induced by minimizing the covariance across seed sources included in the portfolio.

These “bet hedging” approaches above account for some, but not all, of the uncertainty in climate change projection. At present, significant inconsistencies between the projections of respected climate models underscore the difficulty of projecting climate under unprecedented physical conditions (Knutti 2008). Models continue to improve, but important variables for tree growth and survival, such as mean annual precipitation, are not projected consistently between models (Raisanen 2007). Furthermore, there are many ways to weight models in a portfolio and choices about these weightings pose their own risks and uncertainties (Weigel et al. 2010). Ultimately, we make our decisions with the best tools at hand, but we cannot reliably predict the future. This situation may be improved by an adaptive management approach that stresses monitoring, continuous improvement, and course correction as needed.

Procuring Seed

Once a migrated procurement zone has been defined, seeds from that zone need to be obtained. Seed collections for most commercial tree species are carried out on a regular basis from a variety of locations within designated seed collection areas or zones (Morgenstern and Wang 2001). Furthermore, most Canadian provinces have seed orchards, which are intensively managed plantations designed to produce high-quality seed from select genotypes for reforestation. While orchard and wildstand collections currently provide adequate seed supply for most species in most years (Morgenstern and Wang 2001), it is not clear how well this seed production system will function under climate change. For example, if seed production is projected to decline, it may be desirable to establish a system of “migrated” seed orchards at climatically appropriate sites in order to maintain adequate seed production levels.

The projected impact of climate change on tree seed production varies according to the species and weather variables under study (van der Meer *et al.* 2002, Clarke *et al.* 2011). Increased variation in spring temperature has been linked to widespread frost damage, reproductive failure, and mortality in recent years (e.g., Gu *et al.* 2008); such events are likely to increase under climate change (IPCC 2007). However, several studies have reported increased seed production at elevated CO₂ levels (Jablonski *et al.* 2002, Darbah *et al.* 2008), which may (at least partially) counteract the climate-related declines projected for some species. This topic is further complicated by epigenetic effects (described above), which would favour maintaining seed orchards as far south as possible so that resulting seeds/seedlings were suited to warmer temperatures. These issues are at the heart of future seed supply in Canada and clearly warrant closer study; given the substantial timelines involved in altering the current system, it may be prudent to explore them in the near future.

The situation is different for species of conservation concern, which are neither widely collected nor stored in anticipation of large-scale replanting projects. However, Vitt *et al.* (2010) make the case that a concerted and coordinated effort to collect and bank seeds is an essential step in preparing for AM—particularly if climate change tipping points are reached that necessitate sudden conservation action (e.g., Lenton *et al.* 2008). Such collections should follow established guidelines to ensure adequate genetic diversity in the new population (Brown and Briggs 1991, Guerrant *et al.* 2004, Vitt *et al.* 2010). The time and effort required to collect seed and grow an adequate amount of planting stock could be substantial and practitioners would need to factor that into program budgets and timelines.

In Canada, the National Tree Seed Centre⁷ has a goal to collect and store representative samples from throughout the natural ranges of all Canadian tree and shrub species; the Centre currently has germplasm for approximately 100 native species. Such collections provide a measure of insurance in case of species extinctions and may provide seed for conservation and restoration activities. Some species will not tolerate long-term or frozen seed storage (e.g., oak species). The inability to store these recalcitrant-seeded species for long periods creates logistical problems for their use in large-scale AM efforts as seed collection, planting stock production, and planting would need to be closely synchronized.

⁷<http://cfs.nrcan.gc.ca/subsite/seedcentre/home>

As climate warms, optimal seed sources for planting sites in southern Canada will increasingly be located south of the Canada–United States border, thus introducing a geopolitical aspect to AM. All plants and seeds entering Canada from the US require a phytosanitary certificate issued by the United States Department of Agriculture. Furthermore, a plant species that is a known host of an invasive pest also requires an import permit. These requirements may add a modest amount of time and cost to the seed procurement process. In order to secure future seed supply, it may be desirable to establish seed production areas in Canada for some species/populations that would otherwise be imported from the United States. Such an initiative could incorporate breeding materials from existing tree improvement programs in the United States. These considerations should be included in the assessment of future seed supply noted above.

Selecting Planting Sites

The methods presented above for calculating migration and seed transfer distances identify broad areas that are projected to be climatically suitable for deployment of a given seed source under climate change; within these areas, specific planting sites would need to be pinpointed based on fine-scale features such as current land cover, soil attributes, and site topography (Fiedler and Laven 1996, Guerrant and Kaye 2007). For commercial tree species, planting sites are generally determined by harvesting operations that require subsequent reforestation. Resource managers may choose to replant with the same species (but using a climatically appropriate provenance) or a different species (or species mixture) that is well suited to site conditions. Commercial species tend to have well-described site requirements that would assist in making these decisions.

The situation is different for species of conservation concern, for which a network of available planting sites (generated by harvesting activities) would not exist. However, these species often have well-described habitat preferences, which would help to identify suitable microsites within climatically appropriate areas. This process could be facilitated with GIS if high-resolution map layers were available for each habitat component of interest (Vitt *et al.* 2010)—a situation that may not exist for many environmental variables and locations (e.g., soils data in much of Canada are very coarse or absent). Alternatively, suitable planting sites could be identified through a combination of broad-scale land cover maps, aerial photographs, and field surveys. For some species it may be necessary to create a suitable planting site within a climatically appropriate area (Hoegh-Guldberg *et al.* 2008). For example, many forest species require canopy openings in which to germinate and become established; if unavailable, such sites could be created through targeted silviculture operations.

Establishment Considerations

If seed source and planting site have been suitably matched, and the risks of undertaking AM evaluated and found acceptable, planting may proceed. For commercial tree species, planting considerations such as site preparation, seedling spacing, and planting technique will likely follow standard regional guidelines. However, if a portfolio approach (as outlined above) were adopted, practitioners would need to determine the best approach for planting several seed sources at a

single reforestation site. If seed sources were planted randomly across the site, it would allow for competition between seed sources with the best-adapted genotypes eventually dominating the stand. Conversely, planting each seed source as a separate block would facilitate monitoring of the different sources and might allow a source that was not dominant at the start of the rotation to persist until conditions were more favourable for its growth.

For species without conventional best practices for establishment, there are many planting-related uncertainties. Guerrant and Kaye (2007) identify a number of planting considerations associated with plant reintroductions that are also applicable to the AM situation, including size of the founder population, propagule type (seeds versus seedlings), propagule source (wild collected versus genetically selected), site preparation (e.g., removal of competing vegetation and in some cases removal of organic matter at planting spots prior to planting), use of soil amendments, and timing of planting (spring versus fall). The optimal approach will clearly depend on the specific nature of the system (i.e., target species and planting site) under study. In the likely event that some of this information is unknown, Falk *et al.* (1996) suggest that projects be carried out as experiments, designed to elucidate reintroduction best practices for the target system.

Post-establishment Considerations

Tending

For commercial tree species, post-establishment tending (e.g., herbicide treatments for conifer release) should follow established protocols for a given region and species. For other species, tending activities will vary with the system under study. In a review of 10 plant reintroduction projects, Guerrant and Kaye (2007) report five different tending approaches that also apply to AM efforts: watering, weeding, pest/predator control, vegetation management, and none. Due to logistical and financial constraints, many of these activities will not be feasible for many projects. However, documented establishment failures due to competition (Wagner *et al.* 2001), drought (DeMauro 1994), and predation (DeMauro 1994) indicate that some species benefit from tending during establishment. Knowledge gaps around best tending practices may be addressed through an adaptive management approach that emphasizes careful experimentation, continuous learning, and monitoring (Falk *et al.* 1996).

Measurements and monitoring

For commercial tree species, a series of standard silvicultural measurements (e.g., survival, height, and DBH) could be used by forest managers to assess the success of an AM program. For other plant species, which focus on the establishment of self-sustaining satellite populations, measurements could include standard survival and growth estimates as well as measures of reproductive success such as propagule production, number of viable offspring, and total population size (Guerrant and Kaye 2007). A major concern with AM programs is the potential for the relocated species to cause negative impacts at the planting location. Thus, monitoring should also include observations of damage caused to native biota at the planting site and spread beyond the planting site. This is clearly a complex issue because species declines at the recipient location may be due to changes in climate; furthermore,

changes in the relative abundance of species may indeed be a goal of the AM program.

Evaluation of success

The success of a reintroduction effort can be based on biological factors and overall project considerations (Pavlik 1996). In the AM context, biological success refers to the establishment of a self-sustaining and climatically appropriate population, measured using the various indices outlined above. For commercial tree species, growth of the climate-matched seed sources should be compared to the growth of a “control” seed source (i.e., the seed source that would have been planted in the absence of climate change). This could be accomplished by including a control seed source in the portfolio of provenances used at a planting site, or by comparison to a naturally occurring comparable stand in the vicinity of the test site.

Along with the establishment of a productive population of the focal species, successful AM implies a full evaluation of collateral genetic, community, and ecosystem impacts (Richardson *et al.* 2009). Across the entire spectrum of forest management objectives, “success” is not an unambiguous term. In addition to the biotic and economic impact of introducing a new species, AM has inevitable social and ethical dimensions (Camacho *et al.* 2010, Aubin *et al.* 2011). Imagine, for instance, that a commercial tree species has been introduced beyond its native range and has met the criteria for biological success described above. Under these conditions it is possible that the introduced species will spread beyond the targeted plantations where, like any novel species, it will have ecological impact. Some will argue that this scenario illustrates the deliberate introduction of an invasive species. Others will argue that it illustrates the successful management of forest health and productivity, which is traditionally the goal of forest management. Whether human-assisted transition is a net negative or positive compared to the unmanaged species shifts that will accompany climate change is the subject of an ethical debate beyond the scope of this paper (Aubin *et al.* 2011).

Project success is a broader concept that includes spin-off benefits from an AM effort. For example, benefits may include new insights into AM best practices, new knowledge around the biology of a target species, or even an increase in public awareness about AM issues (Guerrant and Kaye 2007). Thus, while an AM project may fail for any number of biological reasons, it may still contribute to forest conservation through the acquisition of new knowledge and experience (see Swaisgood and Sheppard 2010).

Financial Considerations

AM activities *per se* should add relatively little to typical plantation establishment costs. Much of the seed procurement process would continue unchanged under an AM program, with the exception that seed/seedling transportation costs would presumably increase modestly. Given that transportation costs are a small portion of total seed procurement costs (about 6% on average; Sarker *et al.* 1996) and that seed procurement costs themselves constitute only a small portion of total plantation establishment costs (McKenney 1986), increased transportation costs incurred by AM would represent a negligible increase in the overall reforestation budget.

Importing seeds from the United States requires a phy-

tosanitary inspection and, in some cases, an import permit; however, both the inspection and the permit involve only a nominal fee. Thus, although cross-border seed procurement costs would fluctuate with the exchange rate of the Canadian dollar, the added cost associated with seed importation would be small in comparison to other plantation establishment costs.

Establishing seed production areas in Canada for some species should be considered as an alternative to seed procurement from the United States. Canadian seed production would safeguard and provide local control over seed supply. It might eventually be required since climate change will increasingly affect trees and seed production in native US sites. The cost of establishing and maintaining seed production areas in Canada would, at least in the short term, be higher than purchasing seed from suppliers south of the border.

Costs could rise substantially if AM were practised on sites normally left to regenerate naturally. If AM emerged as a preferred approach for climate change adaptation, it may be desirable to expand AM to areas outside of those that are currently artificially regenerated (about 450 000 ha/year; NRCan 2010) and thus hasten the wide introduction of adapted genotypes in a timeframe that reduces the area where significant maladaptation occurs. Candidate areas for this expansion include lands that are currently allowed to naturally regenerate following cutting (~350 000 ha/year) and forest fire (~1.5 million ha/year; NRCan 2010). At plantation establishment costs of \$1400 to >\$3000 per ha (Yemshanov *et al.* 2007, Corlett *et al.* 2010), large-scale implementation of AM on these lands could increase annual costs in the billions of dollars.

To decide whether the cost of undertaking AM of commercial species is worthwhile, it is necessary to estimate its benefits. Models show that AM could play a significant role in mitigating forest productivity losses due to climate change (Beaulieu and Rainville 2005, Wang *et al.* 2006). For example, estimates of rotation-age losses in basal area for eight species established in 2010 at three locations in the western USA average approximately 40% (Crookston *et al.* 2010). A model developed by O'Neill and Nigh (2011) suggests that accrued volume losses due to climate change in lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forests planted in BC in 2011 will amount to approximately 10% at rotation. Equating basal area and volume impacts suggests that, if no action is taken, realized impacts to rotation-age volume could be in the order of 10% to 40%. Even if assisted migration were to mitigate only 25% of these volume losses, the return on investment could be substantial. Furthermore, mitigating volume losses by maintaining forest adaptation would yield additional benefits in non-timber and ecosystem values.

Conservation-oriented AM initiatives would also incur costs that vary widely depending on the scope and intensity of the project. Attaching a dollar value to such initiatives is challenging because economic costs are rarely reported for conservation efforts (Holl and Howarth 2000, Birch *et al.* 2010). In a review of more than 2000 ecological restoration projects, fewer than 5% provided meaningful financial data (TEEB 2009). However, from those studies, an average restoration cost of ~\$2400/ha (USD) was reported for temperate forest habitats. Assuming that conservation-oriented AM costs are similar to ecological restoration costs (which deal with establishing species on previously occupied sites), AM costs could

range from thousands of dollars for small-scale projects (e.g., homeowner/landowner cooperatives) to billions of dollars for large-scale projects (e.g., Yellowstone to Yukon initiative⁸).

Costs could also arise from unanticipated AM outcomes. For example, if a species becomes aggressively invasive at the planting site, control measures may be required. Pimentel *et al.* (2005) review the costs associated with invasive species in the United States and report values for plant control programs that range from several million to billions of dollars annually. Furthermore, heightened monitoring and tending costs may be incurred in an effort to avoid such outcomes. Clearly this is a complex topic involving great uncertainty and potentially huge costs; we present it here to remind readers of the considerable economic risk associated with AM activities. While careful planning and monitoring may help to reduce these risks, there will always be an element of uncertainty when species are introduced into new locations.

Examples of AM implementation in Canada

There are few examples of AM implementation in Canada. In fact, we are not aware of any broadly coordinated AM activities directed toward species of conservation concern. However, several provinces have already incorporated, or are in the process of incorporating, AM into seed transfer activities for commercial tree species. In March 2009, British Columbia (BC) modified its seed transfer standards, allowing seed of most species in most regions to be moved up to 200 m higher in elevation (O'Neill *et al.* 2008b). In June 2010 a second AM policy change was implemented in BC, allowing western larch (*Larix occidentalis* Nutt.) to be moved slightly outside of its existing range to areas where climates are suitable for growth. A working group within the BC Ministry of Forests, Mines and Lands is currently working toward a system of climate-based seed transfer designed to minimize maladaptation, maximize seed deployment opportunities, and accommodate a system of assisted migration in a comprehensive manner for select and wildstand seed sources of all commercial tree species.

In Alberta, seed transfer guidelines have been revised to extend current seed zone limits northward by up to 2° latitude and upslope by up to 200 m. Genecology models, which identify how populations are genetically differentiated in relation to current climate, have been developed from existing provenance trials for white spruce (*Picea glauca* [Moench] Voss), black spruce (*Picea mariana* [Mill.] BSP), lodgepole pine, jack pine (*Pinus banksiana* Lamb.), and tamarack (*Larix laricina* [Du Roi] K. Koch) (Rweyongeza *et al.* 2007, 2010). This information will be used for further assisted migration efforts, should they be deemed necessary. Furthermore, for species such as limber pine (*Pinus flexilis* James) and whitebark pine (*Pinus albicaulis* Engelm.), which currently have no ongoing reforestation programs, collection and long-term storage of seeds has been accelerated with future plans to either reintroduce them in their current habitats or relocate them to new areas where favourable climate exists. In addition, resource managers are exploring options to test non-native species that are anticipated to migrate naturally into Alberta as the climate changes. For example, ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) and Douglas-fir (*Pseudotsuga men-*

⁸<http://www.y2y.net/home.aspx>

ziesii [Mirb.] Franco) are currently being considered as replacements for lodgepole pine, which is being threatened by both climate change and the ongoing mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak.

In Québec, northern sites are being planted using a mixture of seed from local sources and from orchards located in the southern part of the province. This practice is viewed as an insurance policy to help maintain productivity in these northern forests in the event of rapid climate change. Also, transfer functions were recently developed for the major commercial tree species—black spruce, jack pine, and white spruce. Based on these models, two tools were developed to help forest managers make seed transfer decisions. The first, called *Optisource* (Beaulieu 2009), generates maps that show the relative risk of maladaptation associated with transferring a seed source to any location in the province. The second tool is an application of the *BioSim* simulation software (Régnière 1996). It combines biophysical site index, transfer function, and growth and yield models to estimate expected plantation yield for any seed source transferred to any location in the province (see Beaulieu and Rainville 2005 for details).

Ontario has tools to enable AM of several commercial tree species based on transfer functions (e.g., Thomson and Parker 2008) and the focal point seed zone approach (e.g., Parker and van Niejenhuis 1996, Lesser and Parker 2006). The Seedwhere software (McKenney *et al.* 1999) was likewise developed for Ontario with AM applications in mind using the climate envelope approach described above. Recently, research at the Ontario Forest Research Institute has added to the database of long-term provenance performance, focusing on white pine (*Pinus strobus* L.), as well as utilizing controlled environment studies to determine physiological responses to temperature (Eskelin *et al.* 2011). Ontario has not yet altered its forest management seed allocation strategy with climate change in mind, but exceptions to the general rule of matching seed source to current seed zone can be considered on a case-by-case basis.

Many of the other provincial resource management agencies, though not implementing AM *per se*, are actively engaged in AM-related dialogue and initiatives. Typical activities include compiling existing provenance data, remeasuring established provenance trials, and initiating new growth trials aimed at elucidating the growth potential of southern provenances and non-native species.

Concluding Comments

We have outlined the major steps involved in implementing an AM program and assessed, in a general way, the capacity (i.e., state of the knowledge, data, and tools) to carry out each step. Our findings highlight the fact that capacity to implement AM differs between forest species. For example, the existence of established provenance trials, seed transfer guidelines, seed procurement systems, and plantation establishment protocols, makes AM considerably more feasible for most commercial tree species than for most species of conservation concern. This situation is reflected in a number of AM efforts that are already underway in Canada involving commercial tree species.

A number of initiatives could be undertaken to help build capacity for AM implementation in Canada. For instance, the development of an extensive and widely accessible warehouse

of provenance trial data would offer a number of potential benefits for the AM of commercial tree species, including: 1) easier access to data for developing seed transfer models, 2) spatially continuous datasets that extend beyond political boundaries (both provincial and Canada–US), 3) incorporation of older provenance data not currently in digital format, and 4) opportunities to explore broad-scale, multi-species patterns of tree growth in response to climate.

Once an assessment of provenance data is completed, a gap analysis could be used to identify priority areas, species and populations for which additional provenance testing may be required. As Canada's most productive forest land resides close to the Canada–US border, US plant populations located in slightly warmer locations may be the best-suited seed sources for Canada's most productive forests. Given the long time frames required for provenance test establishment and evaluation, it would seem prudent to initiate discussions soon regarding strategies to address this critical need.

It is not clear how well the various seed procurement systems across the country will function under climate change. Given the substantial timelines involved in making changes to these systems, capacity to provide regenerative material for commercial tree species over the next 25 to 50 years should be assessed in the near future. This should also include an assessment of the feasibility of establishing seed production areas in Canada for some species/populations that would otherwise be imported from the United States, thus safeguarding and providing local control over seed supply.

For many species, much capacity-building will be required before AM could be considered a feasible approach for mitigating climate change impacts. A reasonable first step would involve the generation of a list of priority species that may require AM intervention. From there, collecting and storing seed and building knowledge around establishment best practices would be reasonable next steps. Moving forward in these areas may be best accomplished by employing an adaptive management approach that involves careful experimentation, continuous learning, and a significant commitment to monitoring. In the case that these activities are considered prudent conservation measures regardless of climate change, acting on them at the current time (or in the near future) makes sense. However, actions to build AM capacity that involve considerable effort, expense, or risk beyond standard conservation initiatives would likely be best left until further discussion has clarified the appropriate role of AM in biodiversity conservation.

We reiterate that this discussion of AM implementation should not be interpreted as meaning AM is the only, or even a preferred, option for adapting forest vegetation to climate change. Other means of promoting forest adaptation should be explored, regardless of decisions on implementing AM in Canadian forests (e.g., stand improvements that enhance forest health, diversification of species and seed sources in plantations to buffer climate and modelling uncertainty). Nonetheless, we feel there is considerable value in discussing implementation issues at this critical point in the AM debate. In particular, this perspective speaks to the feasibility of AM efforts by raising practical considerations such as the availability of basic knowledge and data, projected timelines, and financial costs. Those on both sides of the debate need to be aware that, except for perhaps commercial tree species, AM

initiatives would likely involve considerable long-term commitment in order to develop capacity and elucidate best practices for plantation establishment, tending, and monitoring.

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