Discussion Paper

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Assisted Migration: Adapting forest management to a changing climate

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Abstract

Forestry practitioners are increasingly interested in how to adapt practices to accommodate predicted changes in climate. One forest management option involves helping tree species and seed sources (populations) track the movement of their climates through "assisted migration": the purposeful movement of species to facilitate or mimic natural population or range expansion. In this paper, we discuss assisted migration as a climate change adaptation strategy within forest management. Substantial evidence suggests that most tree species will not be able to adapt through natural selection or migrate naturally at rates sufficient to keep pace with climate change, leaving forests susceptible to forest health risks and reduced productivity. We argue that assisted migration is a prudent, proactive, inexpensive strategy that exploits finely tuned plant-climate adaptations wrought through millennia of natural selection to help maintain forest resilience, health and productivity in a changing climate. Seed migration distances being considered in operational forestry in British Columbia are much shorter than migration distances being contemplated in many conservation biology efforts and are informed by decades of field provenance testing. Further, only migrations between similar biogeoclimatic units are under discussion. These factors reduce considerably the risk of ecological disturbance associated with assisted migration. To facilitate the discussion of assisted migration, we present three forms of assisted migration, and discuss how assisted migration is being considered internationally, nationally, and provincially. Finally, we summarize policy and research needs and provide links to other resources for further reading.

KEYWORDS: *adaptation; assisted migration; climate change; conservation; ecosystem resilience; forest productivity; risk assessment.*

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Introduction

Fifty years ago, an aerial view of British Columbia's forested landscape on the great interior plateau between Prince George and Quesnel would have shown an impressive, rolling carpet of green, containing a mosaic of ages and dominated by tall, fast growing lodgepole pine. Today, thanks in part to a slight increase in average annual winter temperatures, the same area is a sea of red, orange, and grey trees, standing dead or dying as a result of the mountain pine beetle epidemic.

Could any of us, looking out at that landscape in 1960, have predicted the devastating impacts of the mountain pine beetle? What can we expect to see ninety years from now, by which time scientists have predicted even more substantial increases in average annual temperatures? Will climate change happen at such a rapid rate that trees and ecosystems are unable to keep up? Will we be looking at a landscape of poorly adapted tree species, with commensurate low productivity, compromised pest and disease resistance and poor growth form?

These kinds of questions have fuelled a debate among forest managers and policy makers about the role of adaptation and proactive management in our collective response to climate change. At the centre of the debate is the question: what can we do to keep our forests productive and resilient, to maintain ecosystem services that are vital to our own well-being, and to retain biodiversity? These are all important components of a sustainable forest management framework.

In this paper, we discuss one forest management option—assisted migration—as a climate change adaptation strategy. We begin by providing context: an explanation of how rapidly our climate is predicted to change, how rapid climate change may impact ecosystems, and the body of evidence suggesting that it will be difficult for trees to keep up with predicted changes in climate over the coming decades. We then discuss assisted migration as one forest management option for dealing with climate change, describe perceived risks and benefits of different forms of assisted migration, and identify knowledge gaps, current research, and policy changes needed to implement assisted migration in British Columbia. Finally, we provide links to resources and additional information on this important topic.

What can we expect to see ninety years from now, by which time scientists have predicted even more substantial increases in average annual temperatures?

Climate Change, Species Migration, and Management Options

Predicted Rates of Climate Change and Implications for Forest Ecosystems

After several decades of debate, there is now abundant scientific evidence that global climate change is a reality. The Intergovernmental Panel on Climate Change (IPCC) has concluded that the global atmosphere is warming, and that most of the warming observed over the last 50 years has been caused by the burning of fossil fuels, land clearing, and other human activities that release greenhouse gases into the atmosphere (Gayton 2008). We are starting to see evidence of climate change on the ground, such as earlier spring leafing and flowering in plants (Badeck et al. 2004); changes in species distributions to high elevations (Lenoir et al. 2008); increased wildfire frequency, length, and intensity; and increased survival and expansion of forest pests (TAFCC 2008). In British Columbia, the mountain pine beetle epidemic, the Dothistroma outbreak and the decline in yellow cedar have all been linked to climate change (Carroll et al. 2004; Woods et al. 2005; Beier et al. 2008).

Over the next 100 years, the rate of climate warming is expected to accelerate. While the global warming trend over the last century was around 0.6°C on average, scientists have predicted that British Columbia's climate will warm by somewhere between 1-4°C from 2000 to 2100, with northern British Columbia warming faster than other parts of the province, and the interior warming faster than the coast (Gayton 2008). Precipitation is expected to increase by up to 20%, particularly in the winter, and much more winter precipitation will fall as rain. As a result, we can expect substantial changes to hydrology and reduced growing season soil moisture in some regions (Gayton 2008).

Since climate has long been identified as a primary control factor on the geographic distribution of plant species (Woodward 1987), predicted changes in climate are expected to cause significant changes in ecosystem structure (e.g., predominant vegetation, age class distribution, and species composition), function (e.g., productivity, decomposition, nutrient cycling, and water flows), and distribution within and across landscapes. In British Columbia, a marked redistribution of forest ecosystem climates is anticipated this century (Figure 1; Hamann and Wang 2006).

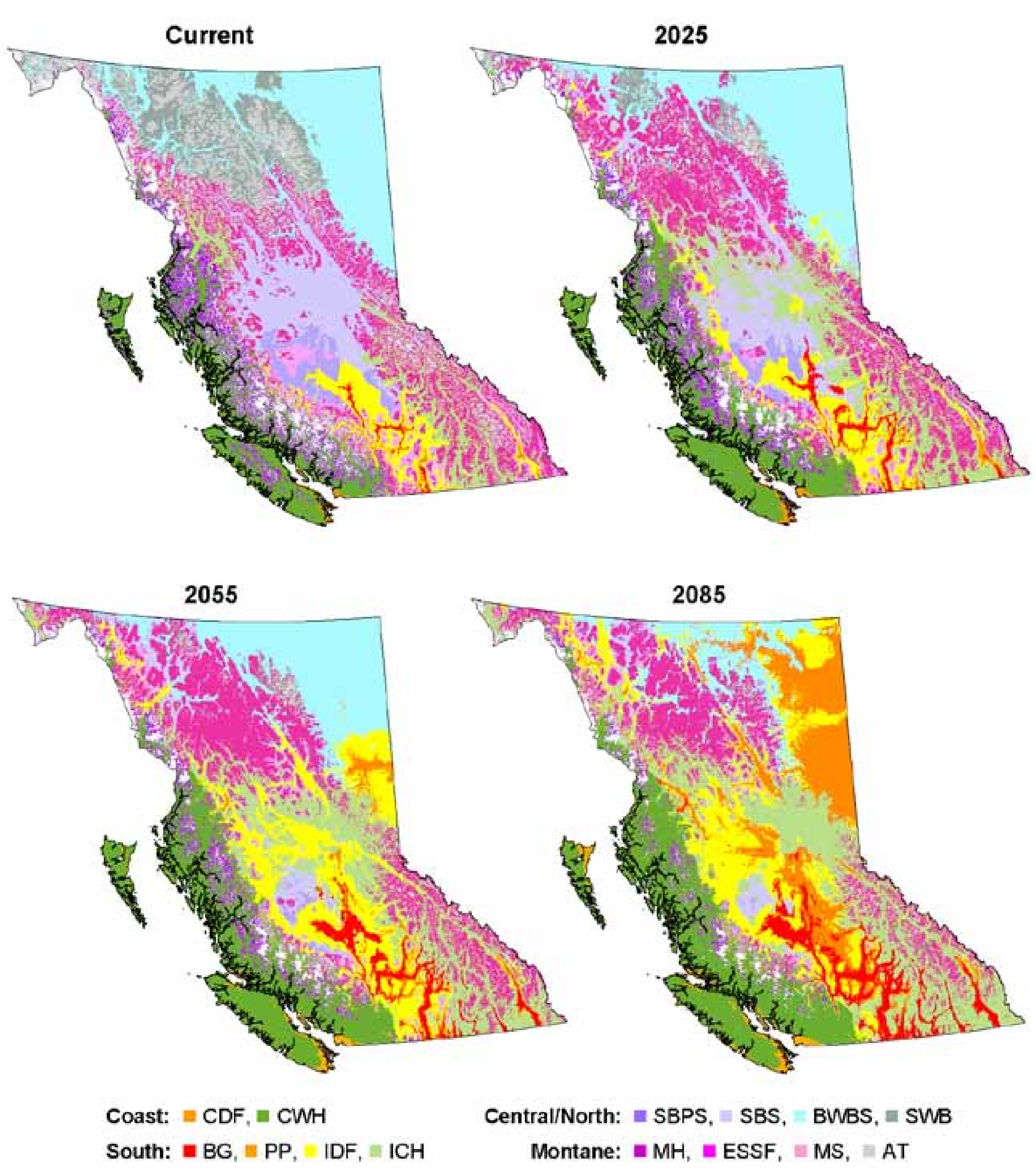

FIGURE 1. Anticipated redistribution of forest ecosystem climates in British Columbia.

Climate change is not a new phenomenon: the trees, ecosystems, and species that exist on our land all migrated from glacial refugia following the end of the last glacial period, about 12,500 years ago. Abundant fossil and pollen evidence indicates that species and populations of species have migrated thousands of kilometers repeatedly while adjusting to past climate shifts. Currently, climate change is occurring at a rate much faster than previous climate shifts (Lefèvre 2010), and most importantly, much faster than trees are able to migrate naturally (Aitken et al. 2008). In an environment that sees a doubling of atmospheric carbon dioxide concentrations over the next century (IPCC 2007), trees will need to move more than 1,000 m per year to keep up with the climate to which they are optimally adapted as it spreads poleward and up in elevation (Aitken et al. 2008). A recent study of five tree species in the eastern United States shows very low probabilities of natural dispersal beyond 10-20 km from current species boundaries by 2100 (an average of 100-200 m per year) (Iverson et al. 2004). It may take several hundred years for species and ecosystems to migrate and re-assort themselves naturally to climates where they are better adapted. In the meantime, widespread ecosystem disturbance can be expected (Iverson et al. 2004; McKenney et al. 2007).

If tree species could migrate with predicted habitat shifts, modelling shows that the productivity of at least six commercial species in British Columbia would increase with climate change, due to a longer growing season (Nigh et al. 2004; Nigh 2006; Wang et al. 2006). However, the authors (Nigh et al. 2004; Nigh 2006) warn that it will take at least 4-5 rotations (240-500 years) before populations have migrated naturally into climates where they are optimally adapted. In the meantime, productivity and health may be significantly compromised. While increased growth rates may be possible in the warmer climates predicted in areas where summer moisture is not limiting, it will only be possible to capitalize on the warmer climates if populations are adapted to those climates.

With the predicted migration lag, trees will be challenged for survival on two fronts: increased abiotic stresses (such as wildfires, summer droughts, summer heat, warm winters, wind storms, and frost damage from sudden temperature fluctuations), and increased biotic stresses posed by increased incidence of endemic insect and pathogen outbreaks, introductions of new pests, and changes to vegetation competition, including from invasive species. These stresses could translate into poor survival (especially at the seedling stage), poor growth and reduced health, poor sexual reproduction and regeneration, and potentially catastrophic losses from fires, insects, and diseases. Williamson et al. (2009) provide an excellent summary of the stresses placed on trees and forests by climate change (see Figure 2 on p.10 of Williamson et. al. 2009).

Assessing the susceptibility of species and populations to climate change is complex because it varies with a number of key factors. At a population level, more northern and continental populations are expected to experience greater rates of climate change. On the other hand, northern populations may be more likely to adapt than populations located at the southern end of a species' range because northern populations will benefit from pollen received from central populations adapted to warmer climates (Davis and Shaw 2001; Matyas 1994). Populations in mountainous regions are expected to fare better because of shorter distances they need to migrate to find suitable climates, compared with populations located in flat topography (Loarie 2009). At the species level, susceptibility can be discussed in terms of a species' ability to track ecological niches through *migration* (a function of seed size, seed dispersal mechanism, and habitat continuity) and adapt to new conditions through *natural selection* (a function of parameters such as fecundity, generation length, genetic diversity, and selective pressures) (Aitken et al. 2008).

Adaptive Forest Management and Climate Change

What does this mean for forest management? In a sustainable forest management framework, foresters are responsible for achieving key forest management objectives, including maintaining forest productivity, forest biodiversity, species at risk, and a number of ecosystem services such as hydrologic function and soil quality. Climate change has introduced a very troublesome complication into this already complex world. With tree migration expected to lag far behind climate migration, it is imperative to adapt our forest management practices to foster resilient ecosystems that continue to provide a range of goods and services, including timber, bioenergy, biodiversity, water, and cultural values. The urgency is heightened by the key role played by trees in mitigating climate change: we need productive forests even more to sequester ever-increasing carbon emissions. As Briony Penn notes, "there is no human invention on Earth that can surpass stomata for sucking carbon out of the air and storing it in wood, leaves and soil" (Penn 2010). Severe maladaptation of our forests could result in Canadian forests becoming a net source of rather than a sink for carbon (Aitken 2003).

Trees will not be able to adapt or migrate apace with changing climates without significant negative impacts on forest health and productivity. Nonetheless, maintaining and promoting genetic diversity and migration capacity in forests may assist their evolutionary potential and help forestall some of the predicted negative consequences of maladaptation (Lefèvre 2010). In a report commissioned by the Canadian Council for Forest Ministers, Johnston and colleagues summarize adaptation measures that could be used by forest managers to help forests maintain productivity in the face of climate change according to five management objectives: reforesting managed forest land, conserving genetic diversity, maintaining species productivity, maintaining forest health, and enhancing adaptive capacity (Table 1; from Johnston et al. 2010).

The primary avenue to enhance resistance, resilience, and adaptive potential of individual species and forest ecosystems is to adapt reforestation activities. Table 1 lists five adaptation measures under reforesting managed forest lands. The top priority option is **assisted migration**, and this is receiving increasing attention as an important adaptation mechanism.

Assisted Migration as an Adaptation Strategy for Climate Change

Assisted Migration Defined

Many definitions of assisted migration—also called managed relocation, managed translocation, or assisted colonization—refer to objectives of protecting rare or endangered species or populations in the face of climate change and other disturbances. However, in the forestry context the objective is most often related to ensuring health and productivity of planted forests. Forest tree species often 'drive' community structure and ecosystem processes (i.e., they are 'foundation' species) (Ellison et al. 2005); therefore, planting forests with trees that are adapted to the climate of their planted environment is fundamental to establishing resilient ecosystems. Consequently, we propose expanding the definition provided by Vitt et al. (2010) to: the purposeful movement of species to facilitate or mimic natural population or range expansion to help ensure forest plantations remain resilient in future climates. The term can be divided into three distinct applications:

- Assisted population expansion (movement of populations within a species' range);
- Assisted range expansion (movement of populations to locations adjacent to the species' existing range, where the population's current climates are expected to reside in the coming decades); and
- Translocation of exotics (inter-regional, transcontinental, or intercontinental movement of species far outside its current geographic range) (Johnston et al. 2010).

To explore assisted migration and the critical debate surrounding its application, it is helpful to break the discussion down into streams: the broader, conservation biology perspective, and the more specific case of applying assisted migration within forestry. In conservation biology, the emphasis is on rescuing species at risk of extinction or extirpation as a result of climate change or other disturbances. Consequently, much of the discussion involves translocation of exotics or assisted range expansion (Ricciardi and Simberloff 2009). In operational forestry, the emphasis is usually on maintaining adaptation of plantations. Consequently, required migration distances are shorter, potentially less risky and, for the most part, supported through extensive provenance testing. Migrations being considered within forest management involve movement between similar biogeoclimatic units and are usually within species' existing ranges. Climatic migration distances under discussion in forest operations (O'Neill et al. 2008; Ukrainetz et al. 2011) translate to geographic distances of approximately 200-400 m up in elevation or up to 300 km northward.

In the subsequent two sections, we describe the application of assisted migration to species conservation and to forestry more specifically.

Application of Assisted Migration to Species Conservation

In the field of conservation biology, assisted migration is proposed as a means of avoiding species extinction predicted as a result of various forms of disturbance including climate change. Species or populations that are unable to migrate to new locations or adapt through natural selection would be intentionally moved to a region, often outside of their current or historic range, where stresses or threats are fewer. The approach is proposed as a conservation strategy for species with poor dispersal abilities in highly modified landscapes subject to the effects of climate change (Willis et al. 2009; Shirey and Lamberti 2010).

TABLE 1. Climate Change Adaptation Measures for Forest Management (Johnston et al. 2010)

Management objective	Adaptation measures
Reforest managed forest land	• Employ assisted migration: including assisted population expansion, assisted range expansion, and/or translocation of exotics • Emphasize species or populations that have the genetic ability to tolerate a wide range of environmental conditions • Reforest immediately after harvesting with most suitable species and genotypes where natural regeneration shows low diversity • Increase species and genetic diversity in plantations to increase the likelihood that some will survive • Establish better-adapted genotypes over large areas of disturbance (e.g., fires, insect outbreaks) • Analyze data from existing provenance tests to understand species and population variability; establish new provenance trials.
Conserve genetic diversity	• Use silviculture systems that maintain genetic and species diversity • Create and maintain corridors to facilitate migration of tree species and genotypes (as well as other plant and animal species) • Create artificial reserves • Use *ex situ* collections to preserve rare populations
Maintain species productivity	• Maintain a diversity of age classes and species where it does not increase susceptibility of insects, disease, or fire • Thin stands on drought-prone sites to reduce water use where it will not increase susceptibility to windthrow or disease • Control undesirable plant species that are likely to become more competitive in a changed climate • Focus management on currently productive sites and those likely to remain productive under future climate and reduce efforts on poor sites • Favour drought-tolerant species in drought-prone areas • Work towards shortening rotation ages and replanting with more robust genotypes • Consider using intensively managed plantations dedicated to wood supply to focus efforts on more productive but smaller forest estates
Maintain forest health	• Enhance forest health monitoring networks to provide early warning signals of impending climate change impacts • Focus harvest activities on stands that are most susceptible to pests, or conduct sanitation cutting in stands that are already affected • Develop genotypes that are drought tolerant and resist insects and disease • Use prescribed burning to reduce fire risk and forest vulnerability to insect outbreaks • Put more effort into integrating climate change models with biological models of phenology
Enhance adaptive capacity	• Share adaptation best practices across jurisdictions • Incorporate knowledge of species vulnerability in decision-making that involves reforestation and silviculture • Encourage changes in society's expectations about forest values and benefits so that they include tree species vulnerability to climate change • Develop technology to make sure of different wood quality and tree species composition • Reduce reliance on historical observations and plot measurements to predict the future • Develop reliable species and stand-level process models for predicting future growth and yield

Consideration of assisted migration as an adaptive strategy to climate change has fuelled a raging debate in the conservation biology literature about whether or not it should be used as a widespread strategy to help species cope with climate change. Many conservation biologists and ecologists consider moving species beyond their current distribution to be too risky, given the myriad of complicated relationships that exist between a species and its environment. However, some biologists are now suggesting the need to re-visit the prohibition of species movement in order to circumvent climate-driven extinction (McLachlan et al. 2007; Richardson et al. 2009). The intensity of the debate surrounds the relative importance of two opposing forces:

- Climate change is predicted to be a primary driver of species extinction (Hoegh-Guldberg et al. 2008; McCarthy et al. 2001; Root et al. 2003; Thomas et al. 2004). In a study published in 2004, Thomas and his co-authors predicted that 15-37% of a sample of 1,103 land plants and animals would eventually become extinct as a result of climate changes expected by 2050. For some of these species there will no longer be any suitable habitat. Others will be unable to reach places where the climate is suitable (Thomas et al. 2004). Whole ecosystems, such as cloud forests and coral reefs, may disappear (Hoegh-Guldberg et al. 2008).
- Moving species without sufficient knowledge of their ecology and how they may interact with climates and other species and other biotic and abiotic factors on novel sites has, in some cases, led to catastrophic invasions of ecosystems by species that are able to reproduce and outcompete native species. The invasive species phenomenon itself is considered a major driver of species extinction (Clavero and Garcia-Berthou 2005), often cited as the second most important driver of species extinction worldwide after habitat loss. Conservation biologists are understandably reluctant to advocate a climate change mitigation strategy that could yield further, irrevocable damage to ecosystems.

Where conservation biologists sit on this debate depends on three main factors: the degree of confidence they hold in being able to predict climate change and future habitat models; the level of ecological knowledge needed to predict the invasive potential for different species, and the relative risk they ascribe to extinction driven by climate versus invasive species (McLachlan et al. 2007).

Proponents of assisted migration emphasize the importance of giving precedence to less hazardous interventions, such as establishment of reserves (*in situ* and *ex situ*), improved connectivity to facilitate migration, and reducing green house gas emissions to curb climate change impacts. But faced with the reality of upwards of 30% extinction rate if current climate change estimates are correct, some conservation biologists have turned to assisted migration as one possible mechanism to prevent catastrophic loss of biotic diversity. They believe that, for some species and some ecosystems, we can gather enough information to safely translocate them to other areas without causing unforeseen consequences, particularly if translocation is done in stages with careful monitoring and adaptive management (McLachlan et al. 2007).

Opponents of assisted migration focus on our inability to predict the impacts of species movement. In a recent opinion article, Ricciardi and Simberloff (2008) suggest that supporters of assisted migration pay too little attention to the importance of evolutionary context and place too much faith in risk assessment. They point to examples of recent conservation-motivated deliberate introductions, such as the introduction of the American red squirrel (*Tamiasciurus hudsonicus*) to Newfoundland to augment the diet of the pine marten (*Martes americana*), which caused near total extinction of the Newfoundland red crossbill (*Loxia curvirostra percna*). This example highlights how difficult it can be to predict impacts of introducing species to a novel environment, because of our limited understanding of complex systems and how ecosystem components and processes are interconnected. Some conservation biologists liken assisted migration to "ecological roulette," suggesting that our lack of predictive power regarding introducing species to locations outside of their historical range should lead to the rejection of assisted migration as a sound conservation strategy under the precautionary principle.

The stage is set for a heated debate on assisted migration policy. In a 2007 review, McLachlan et al. advocate strongly that governments need to develop policy regarding assisted migration, regardless of where they fall on the continuum of opinions on the subject. To further the debate, they outline a framework for moving towards a consensus on the topic, suggesting that we can invoke the precautionary principle while still allowing assisted migration to occur in some cases. They suggest bringing the two camps closer together by implementing a research agenda to inform the development of policy on this issue, and conducting research on important parameters and knowledge gaps such as estimating and monitoring species distributions; and modelling biogeographic conditions, community interactions, long-distance dispersal, and genetic diversity. These research needs are discussed in more detail below.

Hoegh-Guldberg et al. (2008) advance the discussion of McLachlan et al. (2007), arguing that, by increasing our understanding of the habitat requirements and distributions of some species, we can identify low-risk situations where the benefits of assisted migration can be realized and adverse outcomes minimized. They propose a linear decision framework that can be used to outline potential actions under a suite of possible future climate change scenarios, depending on the species in question and the risk of an invasive response. Under their proposed framework, assisted migration and protecting newly established populations are strategies that should be used only when there is a high risk of decline or extinction under climate change, if translocation and establishment are technically possible, and if the benefits of translocation outweigh the biological and socio-economic costs and constraints (Hoegh-Guldberg et al. 2008). These conditions imply that we have sufficient knowledge about each of these factors to facilitate decision-making. Richardson et al. (2009) further the discussion by proposing a heuristic tool that incorporates both ecological and social criteria in a multidimensional decision-making framework. Criteria are summarized in a visual tool that illustrates key dimensions of assisted migration.

When applied to conservation biology as a whole, there is no doubt that assisted migration is considered by many as a risky intervention. However, the specific application of assisted migration within most operational forestry situations is, we believe, a viable forest management option, given the relatively lower risk associated with its use within forest management (i.e., short migration distances into similar biogeoclimatic units), and the need for forest diversification to deal with the inherent uncertainty of climate change.

Application of Assisted Migration to Forest Management

In the operational forestry context, assisted migration usually refers to reforesting harvest sites using neighbouring seed sources adapted to future climates to ensure that plantations remain healthy and productive in future climates. Given that trees will not be able to migrate or adapt through natural selection at a rate sufficient to keep pace with climate change, and that resulting maladaptation will have significant negative consequences including losses in forest health, productivity, and wood quality in coming decades, it seems prudent to intervene proactively, in order to maintain healthy and resilient forests. Thousands of years of natural selection have provided each population of trees with a suite of adaptive traits best suited to its climate (e.g., cold hardiness, drought resistance) and local pests and disease. Recognizing and maintaining these finely tuned natural adaptations by migrating populations to areas that their ancestral climates are predicted to occupy offers an effective, inexpensive, and practical option for addressing climate change.

Current reforestation policy in most jurisdictions, including British Columbia, requires reforestation sites to be planted with seed originating from locations that are geographically proximal to the plantation (Snetsinger 2004). Referring back to the definitions presented earlier, assisted migration in the form of *assisted population expansion* (movement of seed within a species current range) would see this seed use policy (and standards) modified to encourage the use of seed sources of native species from climates anticipated to exist at the plantation in the near future. Depending on the magnitude of the migration distance and the size of the current seed zone, this form of assisted migration may involve little movement of seed beyond its current seed transfer limit—mainly a net shift of seed to colder sites within existing seed zones. Given the long history of successful reforestation and lack of field-based observations or reporting of ecological disturbance associated with current seed transfer standards in the province, ecological impacts of assisted population expansion in British Columbia should be negligible.

Compared with assisted population expansion, *assisted range expansion* (movement of a species outside its current natural distribution) may pose greater risk of ecological disturbance because of the myriad of unknown interactions of the introduced species with the native species (Johnston et al. 2010). Long-term provenance tests that include careful monitoring can alleviate many of these concerns. Regardless of mitigating evidence, if populations are expected to migrate naturally to locations within the species' existing range, it may be pointless from an ecological perspective to preclude assisted range expansion from these areas.

The risk of ecological disturbance posed by *exotic translocation* differs from that of assisted range expansion because the suite of novel species encountered by the introduced species is much greater in exotic translocation than in assisted range expansion. The conservation biology literature is replete with examples of exotic introductions-gone-bad. Fortunately, in the operational forestry context, and in North America in particular, sufficient native species options for reforestation obviate the need for exotic translocation—at least for the foreseeable future.

The mechanism by which assisted migration may be implemented depends on the seed transfer system in use. Seed transfer systems generally fall into two domains: fixed systems, where seed is procured within the fixed boundaries of a seed zone, and focal point zones, where seed for a plantation must be procured from within a defined geographic, climate, or adaptive distance of the plantation. To implement assisted migration in fixed zone systems, zones may stay fixed and seed would be procured from adjacent or climatically suitable zones. Alternatively, more complex analytical techniques and climate modelling may be used to delineate locations where climates of current zones may reside in the future, and seed deployed from the current zone into the future zone. Where focal point seed zones are in use, deployment ranges may be shifted to encourage use of seed from warmer locations and prohibit use of seed from colder locations.

Regardless of the system of seed transfer in use, the climatic distance that seed is migrated may play a significant role on the success of the migration: too short of a migration distance and plantations may experience significant maladaptation toward the end of the rotation; too great of a migration distance and plantations may fail in the establishment phase. Due to the greater sensitivity of trees to stress in early life, a migration distance equivalent to the climate change expected at one quarter to one third of the rotation, i.e., approximately 0.5°C mean annual temperature, has been proposed to balance these competing demands (O'Neill et al. 2008; Ukrainetz and O'Neill 2009; Aitken et al. 2008). However, assisted migration distance must also account for climate change that has taken place over the last several tree generations. As proxy records of British Columbia's climate prior to 1895 are rare, it may be necessary to use the earliest instrument records, which suggest that the mean annual temperature throughout British Columbia has increased approximately 1.2°C over the last 100 years. Therefore, accounting for both recent past and future climate change may require migrating seed approximately 1.7°C (O'Neill et al. 2008; Ukrainetz et al. 2011). As climate change involves multiple aspects of climate (e.g., precipitation variable, extreme event frequency), similar evaluations of multiple climate variables should be used in developing a multi-variate migration distance.

Most opportunities for implementing assisted migration in British Columbia exist where reforestation takes place, i.e., primarily in the Timber Harvesting Land Base (THLB). Since the THLB comprises less than 40% of the province (BC Ministry of Forests, Lands, and Natural Resource Operations 2010), opportunities should also be sought for implementing assisted migration outside of the THLB as new habitat becomes available, to ensure these areas also remain resilient in the face of climate change.

Policy Requirements and Research Needs

Policy Requirements

As a management option in the broader, conservation biology world, assisted migration currently sits in an unregulated zone: most of our existing conservation policies are encompassed within a framework that focuses on preservation and habitat improvement, rather than adaptation and ecological resilience, and do not allow for assisted migration as a viable management option (Camacho 2010). The current lack of legislation makes it easy for individuals to engage in assisted migration; indeed, plant nurseries and garden centres have been introducing species and moving others out of their historic ranges for many decades (Van der Veken et al. 2008). On the agricultural side, it is important to note that plant quarantine policies regulate the transfer of some plant material across national/transnational borders. An improved policy framework is required to help clarify if, when and where assisted migration could be used to prevent extinctions and maintain ecosystem services (McLachlan et al. 2007).

In order to fully implement assisted population and range expansion in forestry, it may be necessary to examine seed transfer across international borders (e.g., northern United States to southern Canada). The introduction of climate-based seed transfer systems is needed as the geographic-based systems of seed transfer currently in use in most jurisdictions do not easily nor effectively accommodate climatically-based transfer distances. Implementation of climate-based seed transfer systems will also facilitate the research and analyses needed to assess the policy and socio-economic implications of assisted migration.

Research Needs

To help determine the types of policies and practices that will work best for species and ecosystems faced with challenging migration requirements in the face of climate change, several key knowledge gaps (noted below) must be filled (McLachlan et al. 2007; Aitken et al. 2008; Johnston et al. 2010). It is noteworthy that projects to address many of these knowledge gaps within forest management are underway in British Columbia (see section below for a detailed summary of British Columbia's initiatives related to assisted migration in forestry).

Improving our ability to make climate change predictions

There is a need to refine climate change models and assess potential policy and socio-economic impacts, risks, and vulnerabilities using climate change scenarios that have a high likelihood of occurring, in order to accurately select species that are suited to future climates. It is also important to identify sources of uncertainty; in many cases, uncertainty may be used as a proxy for risk, because models and predictions may be inadequate (due to a lack of field-based verification and measurement).

Improving our ability to model species distributions under climate change

The confidence with which we can predict species distributions under different climate scenarios must be improved in order to predict range expansions or contractions, changes in growth patterns, changes in productivity, and other factors more accurately. This is particularly important for species with small range sizes, and for threatened or "at risk" populations found along the southern edges of their ranges.

Developing approaches to include other factors into predicted future distributions of species.

Bioclimate envelope modelling assumes that climate is the primary constraint on habitat occupancy, and that species' ranges will migrate together with climate change. However, competition, trophic associations, and mutualisms can also be important determinants of species' ranges. Paired or multi-species assisted migration may be necessary to enable range shifts of dependent species. Some tree species may require mychorrhizal innoculae for germination and growth (McLachlan et al. 2007). Novel, limiting interactions (e.g., predatory or competitive) may also limit success of introduction.

Improving estimates of long distance dispersal

As a key process in range dynamics, long distance dispersal is one of the most difficult aspects of conservation biology to characterize, particularly within fragmented habitats. Improved estimates of long distance dispersal are essential to predict which species require assisted migration intervention, and to help guide when other approaches, such as improved connectivity, could work just as well.

Understanding genetic diversity

Intraspecific genetic variation is frequently adaptive (Etterson 2004) and it is critical to understand and choose wisely the seed sources for assisted migration. For example, in the northern hemisphere, northern populations may be pre-adapted for colonization ability because they contain the genotypes that were successful in the last population expansion. On the other hand, populations from the southern periphery may be a higher priority because these are most at risk from climate change. Establishing multi-species, long-term provenance trials to quantify the climate tolerance of seed sources is critical so that assisted migration strategies can be optimized.

Developing climate-sensitive models for forest management

Climate-sensitive growth and yield models are urgently needed for assessing long-term forest productivity. Predictive tools for assessing ecological impacts of potential new insect and disease infestations and changes in wildfire patterns are also required. Furthermore, there is a need to understand how the frequency of extreme climate events will change, and to incorporate this information into forest productivity, forest health and wildfire models.

Developing protocols for the application of assisted migration in forestry

Applying assisted migration within forestry requires the development of a flexible framework to allow for addressing risk and uncertainty, methods to ensure selected reforestation species and seed sources are best adapted throughout the rotation, and protocols on the magnitude and timing of assisted migration (e.g., how much material to introduce, at what point in rotation should we aim for optimum growth). Monitoring and evaluation protocols are also needed.

International, National, and Local Assisted Migration Initiatives

This section summarizes some of the key assisted migration initiatives that are ongoing across the world, Canada, and locally in British Columbia. The initiatives mainly include either efforts to inform assisted migration policy, or active assisted migration programs.

International

International Union of Forest Research Organizations (IUFRO)

In an effort to provide objective and independent scientific assessments of key issues in order to support more informed decision-making at the global level, IUFRO has launched the "Global Forest Expert Panels" initiative. This initiative uses thematic Global Forest Expert Panels to carry out assessments. Their first assessment, Adaptation of Forests and People to Climate Change, contains an analysis of adaptation measures that could be applied on a global basis to help forest communities adapt to climate change (Seppala et al. 2009).

Torreya Guardians

Assisted migration is being applied to rescue *Torreya taxifolia*, an endangered conifer tree with a range currently restricted to the eastern bluffs of the Apalachicola River, extending approximately 35 km in northern Florida and less than 1 km into southern Georgia. Without intervention, the species is predicted to be extinct by 2100. The Torreya Guardians website contains a wealth of information on the topic of assisted migration, focused in particular on exotic translocation of *T. taxifolia*.

US Forest Service

A high-level task force in the United States is currently investigating adaptive responses to climate change along three predominant themes: building ecosystem resistance to climate change stressors, increasing ecosystem resilience in recovering from severe disturbances resulting from climate change, and facilitating landscape scale ecosystem transitions in response to changing environmental conditions. The third response includes assisted migration as a possible adaptive management tool. Forest Service Chief Tom Tidwell explained the overall approach being considered by the US Forest Service in a recent speech, the text for which can be accessed online (US Forest Service 2010).

Taskforce on Adapting Forests to Climate Change

The Taskforce on Adapting Forests to Climate Change (TAFCC) is a group of scientists and land managers that are particularly interested in understanding the potential effects of climate change on natural and planted forests in the western United States. Their work includes collaborative projects on forest adaptation to climate change, including Douglas-fir provenance trials; decision support tools for determining appropriate provenances for future climates; and developing a climate-driven version of Forest Vegetation Simulator (FVS), a forest dynamics model used by forest managers to simulate the effects of management. They have also developed a seedlot selection tool to help forest managers match seedlots of planting sites based on climatic information. See the Taskforce on Adapting Species to Climate Change website.

Suitability Atlas for Woody Plants on the Iberian Peninsula

Researchers from Universitat Autònoma de Barcelona (UAB) and the Centre for Ecological Research and Forestry Applications (CREAF) have developed the Suitability Atlas of Woody Plants of the Iberian Peninsula, a series of digital maps available online which for the first time reveal the present and future degree of adaptation to climate conditions of the main plant species found in the forests throughout the Iberian Peninsula. Available at the Atlas of Woody Plants of the Iberian Peninsula website.

Canada

The Canadian Council of Forest Ministers recently established a national study of forest sector adaptation to climate change. The study is planned using a phased approach that will assess the consequences of climate change and variability on the physical, biological, and socio-economic systems that make up the Canadian forest sector (Johnston et al. 2009). The study includes an assessment of the vulnerability of major commercial tree species in Canada to climate change; identifying expected impacts of climate change on forest ecosystems across Canada; and an assessment of the vulnerability of human systems to changes in forest ecosystem services and values. The results of the first phase (Johnston et al. 2010) identify assisted migration as a leading adaptation option. A series of extension notes aimed at forest managers on the topic of assisted migration is expected to be available online by the end of 2011.

British Columbia

Assisted Migration Adaptation Trial (AMAT)

In 2004, staff at the Ministry of Forests' Research Branch established the first large-scale provenance test specifically to examine population responses of Interior spruce to climate change. Subsequently, in 2006, they began planning a large-scale assisted migration adaptation trial (AMAT), to inform the use of assisted migration as a climate change adaptation strategy. Seedlings from populations of 15 species from British Columbia and neighbouring US states are being planted at 48 reforestation sites from southern Yukon to northern California. Tree growth and health will be monitored and related to the climate at the plantation site. Information from the trial will greatly enhance the ability to identify species and seed sources best adapted for current and future climates. The information from these trials will be used to revise British Columbia's tree species selection guidelines and seed transfer standards, helping to foster resilient, healthy, and productive forests well into the future. See the BC Ministry of Forests' Assisted Migration Adaptation Trial website.

Amendments to Seed Transfer Policy

A recent study examined opportunities for interim measures for assisted migration of tree seed in British Columbia by assessing the climatic transfer distance associated with elevational transfer of seed (O'Neill et al. 2008). The report recommended increasing the upper elevation limits of most orchard seed zones and the upward elevation transfer limit of wildstand seed transfer distances of most species by 100-200 m. The recommendations were implemented in 2009, and represent one of the first examples of seed use policy changes intended to address climate change in a forest management context in Canada.

A subsequent change to seed transfer policy in British Columbia allows for limited use of western larch beyond its contemporary range, in areas projected to be climatically suitable in 2030. This amendment, which came into effect in June 2010, is the first of its kind to enable assisted range expansion. The amendment was based on research which used information from forest resource inventory plots, existing western larch provenance trials, and various climatic projections to pinpoint areas having high probability of healthy and productive growth of western larch in the future (Rehfeldt and Jaquish 2010).

Development of a climate-based seed transfer system

An initiative is underway in the Tree Improvement Branch of the Ministry of Forests, Lands, and Natural Resource Operations (FLNR) to convert British Columbia's geographic-based seed transfer system into a climate-based system so that it can more effectively accommodate assisted migration. The new approach is intended to ensure that each plantation receives the seed sources best adapted to the site's climate while maximizing the area each seed source can be used, and will facilitate implementation of assisted migration in a comprehensive and effective manner.

Conclusion

Assisted migration represents an important tool for helping plant and animal populations, communities, and ecosystems as a whole respond and adapt to predicted ecosystem shifts within a changing climate. Assisted migration may be especially important for species and ecosystems with restricted ranges, which may be physically unable to migrate to new habitat as it becomes available. In order to use assisted migration, either as a general conservation biology strategy, or as a response to climate change within forest management, it is critical that we do so with due diligence, within a framework that allows for flexibility, uses best available science and predictive tools, considers risk and uncertainty, and evaluates and monitors results to ensure that unintended consequences are minimal.

Our assessment of the risks of migration versus no migration favours the use of assisted population and range expansion in British Columbia, within a forest management context. Extensive experience with provenance testing in British Columbia helps to mitigate many of the concerns associated with these two forms of assisted migration. Use of assisted migration should be complemented with other climate change adaptation strategies, particularly those aimed at facilitating natural migration and natural selection (Johnston et al. 2009, 2010).

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Test Your Knowledge . . .

Assisted Migration: Adapting forest management to a changing climate

How well can you recall some of the main messages in the preceding Discussion Paper? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. Of the three types of assisted migration distinguished in this paper, which is the type most commonly applied within forest management as a climate change adaptation strategy?
   a) Translocation of exotics
   b) Assisted population expansion
   c) Assisted range expansion

2. Which factors increase a tree species' susceptibility to climate change?
   a) Restricted species range
   b) Short seed dispersal distance
   c) Long generation time
   d) Fragmented landscape
   e) Flat landscape

3. For which species has the BC Ministry of Forests, Mines and Lands most recently changed seed transfer standards to facilitate assisted migration?
   a) Douglas-fir
   b) Interior spruce
   c) Western larch
   d) Trembling aspen
   e) Western redcedar

Answers

1. B 2. All of the above 3. C