Species choice and seed sourcing for forestry field experiments to address climate change across Canada

by

Genevieve Meree Dorrell

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in
Forest Biology and Management

Department of Renewable Resources
University of Alberta

Abstract

Climate change adaptation in forestry will need field tested climate-informed seed transfer strategies to improve resilience, preserve genetic diversity and ensure long-term health and productivity of forest ecosystems. This is especially urgent in northern latitudes, such as Canada, where warming trends have been most pronounced. The large-scale DIVERSE research project plans to establish such assisted migration trials at 22 forest management areas across Canada with provincial government and industry participants in British Columbia, Alberta, Ontario, Nova Scotia, Quebec, and Saskatchewan. We contribute an on-line decision support tool to help the DIVERSE researchers and forest managers make climate-informed selections of tree species and seed sources for reforestation. These recommendations include cross-border transfers and can also include introducing new species beyond their current range limits.

For the climate-informed seed sourcing recommendations, I used the scaled multivariate Euclidean distance of 12 bioclimatic variables to match seed source's historic climate to planting site's new projected future climates, where source and targets were defined by ecosystem delineations for Canada and the US. Climate suitability of a species for a target site in the future was inferred by averaging species' frequencies of the five ecosystems with the closest climate distance. This resulted in climate matched source ecosystems and species frequencies for the 2020s, 2050s and 20280s for all the ecosystem delineations. This is a lot of information to communicate so a web tool (http://tinyurl.com/DIVERSE-SST) was developed for the forest companies and government stakeholders across Canada that participated in this project.

This Euclidean distance ecosystem-based climate matching approach is a fairly basic type of species distribution modeling. However, the simplicity of this approach allowed me to

incorporate over 240 of the major tree species in North America in the recommendations. Additionally, the larger geographic scale of the climate matching provided recommendations at a level more in line with current seed sourcing systems making the recommendations more operationally relevant. These recommendations are the first step in the establishment of test plantations to validate whether tree growth, health and survival can be maintained or improved through large scale operational deployment of assisted migration in Canada.

Preface

A version of this thesis is being prepared for submission as a journal article entitled: Dorrell, G., Hamann, A., Boyce, N., Zimmerman, Z., Solarik, K.A, and Messier, C. "*Species choice and seed sourcing for forestry field experiments to address climate change across Canada*". CM, AH, KAS and GD conceptualized the research, GD developed the methodology, carried out the analysis and designed the figures and tables, with feedback and advice from AH and KAS. NB developed the backfill forest cover model to remove human development. AH programmed the web tool with input from GD, NB, ZZ, KAS and CM. GD wrote the first draft of the manuscript, edited by AH.

Acknowledgements

My time at the University of Alberta and my involvement in the trans-Atlantic forestry master's program has been a fulfilling challenge.

First, I would like to first thank Professor Hamann for his mentorship and continued belief in me. His advice and expertise were integral to the completion of this thesis. Additionally, his steadfast leadership of the Trans-Atlantic Forestry Master's program helped me not only complete the requirements for both degrees but also made me feel supported throughout the process. Secondly, I would like to thank the DIVERSE project for funding this important work and bringing this gap in scientific knowledge and communication to us, so we could conceive of this project. I would also like to acknowledge Nicholas Boyce's contribution. He created the back filled prediction of forest cover in North America without human deforestation that was used in the calculation of the species recommendations.

I would also like to acknowledge my friends, old and new; particularly the members of the SIS Lab who often kept me company while I worked to meet tough deadlines. I also want to thank my fellow Trans-Atlantic Forestry Masters peers for their support when I was writing my thesis in Vienna while managing a busy class schedule. I would not have made it through my first month in Vienna without you. I would also like to thank all my professors at University of Alberta and BOKU for their engaging lectures and patience as I took my first forestry classes. Lastly, I would like to thank the staff at the Department of Renewable Resources at the University of Alberta for their help and for fostering such an inclusive learning environment. Completing this thesis would not have been possible without all the support and encouragement I received so thank you.

Table of Contents

List of Tables

List of Figures

1 Introduction

Long-lived species, like trees, take centuries to millennia to adapt to a new climate through evolution (Beaulieu and Rainville, 2005; Ledig et al., 2012). They also have limited migration capacity with average range expansion rates of only hundreds of meters per year, which historically has allowed for moderate shifts over millennia in response to past climate change (Delcourt and Delcourt, 1987; King and Herstrom, 1997; Ritchie and MacDonald, 1986). However anthropogenically caused global warming is expected to occur at a rate not previously observed in geologic time (Lee et al., 2024), which would require trees to migrate at a rate six to ten times previously observed under the most optimistic circumstances (Aitken et al., 2008; Davis and Shaw, 2001; Lemprière et al., 2008; Malcolm et al., 2002; Williams and Dumroese, 2013). Researchers predicted that in most circumstances trees would not have enough time to genetically adapt or migrate with the changing climate (Beaulieu and Rainville, 2005; Chmura et al., 2011; Ledig et al., 2012; Lo et al., 2011; McKenney et al., 2009), and now forest inventories are revealing that species on the eastern coast of North America are already failing to track climate change (Sittaro et al., 2017; Zhu et al., 2012). Manifestations of maladaptation due to this lag have started to become apparent in recent decades. Despite being adapted to wildfire, boreal forests in western Canada (Whitman et al., 2019) and pine forests in the southwestern US (Coop et al., 2016) are struggling to regenerate after fire due to climatically driven increased drought and shorter wildfire return intervals. Increased drought mortality across Canada has also reduced carbon sequestration causing a potential climate feedback effect (Liu et al., 2023).

Assisted migration, i.e. actively moving seed sources to new planting locations with appropriate climate conditions through management, could be an important strategy for preserving the health, productivity and genetic diversity of North America's forests in a warming world (Jump and Peñuelas, 2005; Vitt et al., 2010). Assisted migration field experiments in North America have yielded promising results for white spruce (Otis Prud'homme et al., 2018), two oak species in Minnesota (*Quercus macrocarpa* and *Quercus rubra*) (Etterson et al., 2020) and the culturally significant monarch wintering tree *Abies religiosa* in Mexico (Carbajal-Navarro et al., 2019; Gomez et al., 2010) to name a few. Currently, after timber harvest, replanting is standard practice in Canada and the US, so replacing local seed sources with panting stock that is better adapted to the planting site's new climate could be implemented operationally at a large scale with little additional effort or cost.

However, seed movement is normally legislatively restricted through seed zone delineations or breeding regions, because moving trees too far outside their adapted climate niche has historically resulted in reduced growth and survival. Seed zones are often derived from ecosystem delineations, especially for non-commercial tree species (Bower et al., 2014; "NRC (2006) Natural regions and Subregions of Alberta," n.d.). While many commercial species have dedicated seed zones like white pine in the Pacific Northwest (Campbell and Sugano, 1989). Seed zones generally attempt to delineate genetically homogenous populations of trees at as large a geographic scale as possible, so seeds can be transferred as far as possible without concerns of maladaptation.

However, the implied assumption of seed zones that climate is constant is no longer true (Lee et al., 2024). We now need to calculate new climate informed seed transfer guidelines for assisted migration experiments. So, researchers in North America are analyzing tree species' climate tolerances by repurposing provenance trials and long-distance seed transfer experiments, originally designed to optimize tree growth (Park and Rodgers, 2023). Provence trials across a climate gradient can be used to model the relationship between a population's growth and climate variables. To help illuminate this relationship further, new provenance experiments have also been established to specifically address climate change. For example, in British Columbia, a large scale Assisted Migration and Adaptation Trial (AMAT) covers 15 native species at 48 different sites in western North America to test comparative species population performance along climatic gradients (O'Neill et al., 2013).

Figure 1. The DIVERSE project participants' 22 forest management areas across Canada where assisted migration trials will be established

DIVERSE is Another new large-scale assisted migration trial project with provincial government and industry participants in British Columbia, Alberta, Ontario, Nova Scotia, Quebec, and Saskatchewan (Figure 1). However instead of planting populations along a climate gradient, a task that would be to operationally taxing for a project of this scale, they instead plan to test assisted migration recommendations directly at their partner's planting sites (Figure 1). The DIVERSE project is particularly interested in functional diversity so, the DIVERSE project needs climate informed seed sourcing as well as comprehensive species recommendations at a continental scale. Providing the DIVERSE project with these recommendations is the aim of this thesis.

Calculating assisted migration seed sources requires matching the new projected climate at a planting site with the historic climate that planting stock is adapted to. There are currently two decision support tools that facilitate this type of climate matching for all of North America (McKenney et al., 1999; St. Clair et al., 2022). Both tools compare the planting site's new projected climate to the historic climate at a rasterized scale and then the user can layer this rasterized output with current seed zones to determine commercially available seed sources. Additionally, both tools do provide assisted migration recommendations for some species where prevenance trial data was available but, neither provide comprehensive species recommendations like the DIVERSE project requires. Additionally, while layering seed sourcing delineations on top of rasterized output is good solution for calculating assisted migration recommendations for a few planting sites, this individual analysis is not feasible for recommendations at scale the DIVERSE project needs. These limitations forced us to implement a simpler solution.

Instead of climate matching at the pixel level we climate matched at the ecosystem and seed zone level, using a simple multivariate Euclidean distance for climate comparison. Although this ecosystem-based climate matching approach is a fairly basic type of species distribution modeling for which a variety of advanced methods exist (Araújo and Peterson, 2012), this simpler approach is easier to communicate because it produces recommendations for seed transfer from specific origins to specific targets at the geographic scale of current seed sourcing systems. Additionally, by using ecosystem delineations in combination with ecosystem derived forestry specific seed zones we were able to include non-commercial trees species without seed zones as well as facilitate the range expansion of commercial tree species to locations where seed zones have not yet been delineated (Linyucheva and Kindlmann, 2021). Climate matching at a larger geographic scale also helped us provide comprehensive species recommendations. Deciding what species to plant over time requires the analysis of a species favorable climate over time at a planting site and this can be implied by the species frequencies of the planting site's climate matches. However, if climate matching is done at a smaller scale that is a lot of information to calculate computationally but more importantly it is a lot of data to communicate for each climate match. So again, climate matching at a large scale made the species recommendations less computationally demanding and most importantly easier to communicate. Additionally, this approach does not require population specific experimental data from progeny or provenance trials, although such information can be integrated as additional layer as shown by O'Neill et al., (2017). This chosen approach combines methodological elements of a proposed seed transfer system for British Columbia (O'Neill et al., 2017), and ecosystem-based provisional seed zones for native plants for the United States (Bower et al., 2014).

In this thesis, I aim to contribute an analysis with the overall objective of building a general framework to support climate-informed species choices and seed sourcing. Because the chosen methodology does not make use of species-specific provenance test data, or assisted migration trials, the seed transfer recommendations from this research should be considered provisional, and they are specifically meant to support the establishment of test plantations as opposed to recommending operational scale assisted migration prescriptions. My specific objectives include the following:

(1) Use climate habitat suitability modeling to infer future habitat of tree species under climate change to support viable species choices for reforestation.

(2) Provide tabular summaries for the forest management areas of stakeholders of the DIVERSE project, listing which species would be best suited and most relevant in the long term for their holdings.

(3) Develop an ecosystem-based climate matching approach to match target sites with potential seed source locations that contain the preferred species for reforestation.

(4) Provide this information through an on-line seed selection tool for the forest management areas of stakeholders of the DIVERSE project.

2 Literature review of assisted migration

This is a literature review of assisted migration and the methodologies used to calculate seed sourcing recommendations for climate change adaptation experiments in forestry, with a focus on first Canada and then North America. I additionally take a closer look at habitat suitability modeling methodologies in general.

2.1 History of assisted migration in forestry

Humans have been shaping forested ecosystems for thousands of years by moving seeds around. There is evidence that prehistoric Aboriginal groups in Australia intentionally dispersed

Castanospermum *australe* (Fabaceae), a culturally significant riparian tree species (Rossetto et al., 2017). In eastern North America there is evidence that indigenous communities planted and extended the ranges of fruiting trees such as oak (*Quercus*), hickory (*Carya*) and chestnut (*Castanea*) (Abrams and Nowacki, 2008). In the last few hundred years the modern field of forestry has developed, and it also has a rich history of intentionally migrating seeds, usually with the purpose of maximizing timber production (Bennett, 2015; Brus et al., 2019; Hirsch et al., 2020; Kellison et al., 2013; Myking et al., 2016). Now with rapid anthropogenically caused climate change, foresters are looking to again move seed sources but this time to preserve ecosystem function as well as timber production by using southern seed sources more adapted to the changing climate. In the modern context of forest science, this practice is referred to as assisted migration. This was first proposed as a conservation strategy for long lived less mobile species like trees in 1985 by Peters (Peters and Darling, 1985; Williams and Dumroese, 2013) and coined species translation (Griffith et al., 1989). The initial suggestion for assisted migration was met with "the ethical question of whether to deliberately manage natural systems or allow them to adapt on their own." (Aubin et al., 2011; Pelai et al., 2021). Western science has historically separated human intervention from the "natural order" of the ecosystems. I argue that humans were always a driving influence on the ecosystems around us even in North America (Rossetto et al., 2017) and that this is especially true in the Anthropocene era with the greenhouse gas fueled rapidly changing climate. Now 40 years later, as the impacts of climate change intensify interest in assisted migration is growing. Recently, researchers have even suggested moving pollen as a form of assisted migration (Chludil et al., 2025). It has also been suggested for urban foresters due to the harsher conditions of the city scape (Fontaine and

Larson, 2016) and there is evidence it could even be helpful for preserving the biodiversity of forest herbs (Van Daele et al., 2022).

2.2 Development of seed sourcing in North American forestry

Now, before providing new climate based seed sourcing guidelines it is important to understand the current seed sourcing methodologies. Seed transfer guidelines were developed because foresters noticed that planting seed sources too far from their origin resulted in decreased growth and survival ("BEC Map," n.d.; "NRC (2006) Natural regions and Subregions of Alberta," n.d.; Campbell and Sugano, 1989; O'Neill et al., 2013). As early as 1930 in the United States regulations on seed sourcing distances were proposed (Bates, 1930). From there guidelines and then regulations developed at the provincial and regional levels, first from field observations, and then later provenance trials and genetic data (O'Neill et al., 2017). Now in North America seed transfer guidelines and regulations are common practice for most forested areas in the US and Canada. And most regional areas have developed tools to help with seed selection based on the principle that local seed sources are best ("BEC Map," n.d.; "NRC (2006) Natural regions and Subregions of Alberta," n.d.; Bower et al., 2014; Campbell and Sugano, 1989; O'Neill et al., 2017).

Fixed seed zones are a common seed transfer system. Seed zones are defined areas (geospatial polygons) where seeds can be transferred within but not between. There are also focal point seed transfer systems. These systems provide guidance based on how far away the seed source is in elevation and latitudinal and longitudinal distance from the planting site. British Columbia's seed transfer system is a combination of fixed seed zones for seed orchards and mixed fixed and focal point guidelines for natural stand seed sources (O'Neill et al., 2017). Washington and Oregon have species-specific fixed seed zones with more granular elevation transfer guidelines (Campbell and Sugano, 1989). Alberta on the other hand uses its most granular ecosystem delimitations as seed zones ("NRC (2006) Natural regions and Subregions of Alberta," n.d.). Ecosystems are often the starting point for the delineation of seed zones where none exists (Johnson et al., 2004). The regional scale specificity of seed zones means coordination will be required for assisted migration. Providing seed sourcing recommendation at the local seed sourcing level could facilitate the implementation of assisted migration with little additional cost because replanting after harvest is already standard practice in Canada and the US.

2.3 Risks of assisted migration in Forestry

However, the current, local is best, seed sourcing guidelines highlight that there is of risk involved in seed transfer and assisted migration is no exception. When considering assisted migration, the risk of no action must first be weighed against the risk of intervention (Aitken et al., 2008). A 2010 (15 year old) global review of drought and heat-induced tree mortality revealed that climate change could already be increasing background tree mortality rates and die-off (Allen et al., 2010). In Canada increased disturbances like wildfire and bark beetle highlight the maladaptation of forests (Bentz et al., 2010; Coop et al., 2016; Gauthier et al., 2015; Whitman et al., 2019) . I argue that for long lived slow migrating species like trees the risk of inaction likely outweighs the risk of intentional and ecologically informed assisted migration, because once genetic diversity is lost for long lived species it can take millennia to redevelop (Aitken and Bemmels, 2016; Hampe and Petit, 2005).

There are three types of assisted migration with different levels of risk that Researchers usually differentiate between (Leech et al., 2011; Winder et al., 2011). The least risky type of assisted migration is assisted population migration, planting non-local seed sources but still within the species' existing range. The second type is assisted range expansion, planting species outside of but still adjacent to their existing range. Assisted range expansion is a bit riskier due to the possibility of different soil quality and community compositions outside of the species existing ranges. Lastly, the most extreme version is translocation of exotics, planting trees far outside their current geographic range: inter-regional, transcontinental, or intercontinental seed transfer (Johnson et al., 2013). Our recommendations only include the native tree species in North America and focus on the first two types of assisted migration. Only focusing on the first two types of assisted migration reduces the risk of migrated species disrupting the current ecosystem and in the worst case becoming an invasive species because plants are the least prevalent intracontinental invasive species taxonomic group (Mueller and Hellmann, 2008). Additionally in North America there are already so many native species to preserve, and choose from for assisted migration experiments, so translocation of exotics in this case is risky and unnecessary. Also, the DIVERSE project is focused on native North America species. Therefore, for this review I focus on the first two types of assisted migration.

When considering the two less ecologically risky versions of assisted migration a more relevant obstacle to implementation of assisted migration than invasive risk is that it might not be successful (Girardin et al., 2021; Grady et al., 2015). A recent study using the LANDIS-II model found that assisted migration could improve forest productivity under moderate climate change scenarios, but its effectiveness declined significantly in more extreme climatic change scenarios (Gustafson et al., 2023). One mechanism that could be contributing to this finding is that there is evidence that there will be a rise in novel climates as climate change intensifies (Williams and Jackson, 2007). While the majority of these novel climates are expected to be in tropical and subtropical regions where it will be hotter than any existing ecosystems are adapted to, if the transfer distance is limited 500 km, as climate change increases so does the risk of novel climates throughout North America (Williams and Jackson, 2007). This means there simply might not be a viable seed source for assisted migration, within a species range. Additionally, even if the climate is not novel there still might not be a viable forested seed source. For example, A recent paper used provenance data in Spain to simulate Scots pine growth in an extreme emissions scenario and found that traditional seed sourcing was just as successful as climate informed seed sourcing because there was a lack of forested climate matched seed sources (Notivol et al., 2020). Additionally, the planting window could be quite small if climate zones shift at the rate predicted (Gray and Hamann, 2013). Another critique is that assisted migration seed sourcing recommendations are usually based on climate data alone and there are other factors besides climate that could affect success including novel biotic interactions, current necessary tree associated species and different soil qualities at the edge of species ranges (Winder et al., 2011). Additionally, if the assisted migration seed sources are maladapted but survive and breed with local populations, they could reduce the local adaptation of the current trees through gene flow (Lenormand, 2002). That is why field experiments of climate matched seed sources, like the ones being implemented by the DIVERSE team, are an important second step before operationalizing assisted migration to mitigate ecological and financial risk.

2.4 Obstacles to assisted migration implementation

Assisted migration was first proposed 40 years ago and as the impacts of climate change intensify there is growing interest in it as an adaptation measure (Dumroese et al., 2015; Koralewski et al., 2015; Sáenz-Romero et al., 2020; Williams and Dumroese, 2014). There are field experiments indicating its possible efficacy (Taïbi et al., 2016; Young et al., 2020). Yet there is limited larger scale implementation. The first obstacle to implementation is a lack of reliable seed source guidelines for assisted migration (Aubin et al., 2011; Palik et al., 2022; Royo et al., 2023; Stanturf et al., 2024). This is partially due to a lack of field research because climate matched seedlings ideally should be tested in the field before the recommendations are operationalized (Royo et al., 2023). This is further complicated with short planting windows. Additionally, it is not just the current seed sourcing technology but other forestry management tools like growth and yield models that assume a stable climate (Stanturf et al., 2024). This means that a lot of the forestry management tools will need to be redeveloped to provide climate informed predictions. That being said, local silvicultural knowledge is still invaluable for assisted migration implementation. Climate informed assisted migration seed recommendations usually do not consider biotic interaction and site factors; local silvicultural knowledge and planting guides from both the seed source and planting site can be used to bridge that gap (Park and Talbot, 2018).

Another obstacle to implementation is that the current policy around seed sourcing often does not allow for assisted migration. Current seed sourcing policy is country and region specific. In the US assisted migration is legally very narrowly allowed (Aubin et al., 2011; Johnson et al., 2013). While in British Columbia for larch assisted migration has already been implemented as an extension of best practices, because it was for conservative and was based on extensive genetic data and field experiments supporting the policy change (Klenk, 2015). Effective and coordinated assisted migration would require cooperation and integration of multiple regional seed sourcing schemes, researchers and government institutions. Which is what this project hopes to work towards with continental scale assisted migration recommendations and the seed sourcing tool for DIVERSE field experiments.

2.5 History of habitat suitability modeling

Habitat suitability modeling has its origins in historic distribution observation (Schimper, 1902), and the conservation of animals like the black bullhead fish, *Ictalurus melas* (Stuber, 1982). However, in forestry, habitat suitability modeling has its origins in provenance selection for increased yield (Bourdo Jr, 1955; Pecchi et al., 2019). As research about climate change advanced and became more widely accepted, researchers attempted to model the connection between distribution data and climate (Booth, 2018; Pecchi et al., 2019; Rathore and Sharma, 2023). Habitat suitability modelers started to focus on predicting range shifts (e.g., how tree species distributions might change under different climate scenarios). This lead to researchers assessing risk by identifying species with shrinking habitat (Gray and Hamann, 2013; Hamann and Wang, 2006; Iverson et al., 2019; Rehfeldt et al., 2006), determining what species could benefit from assisted migration (Benito-Garzón and Fernández-Manjarrés, 2015), and analyzing the effects of climate and disturbance on ecosystem change (Schneider et al., 2009). All these use cases have resulted in prolific literature about habitat stability modeling. In google scholar the search for forest &"species distribution modeling" returns 22.500 results.

However, the majority of these papers are focused on answering the question of what will happen to the landscape in the predicted new climate (Martínez-Minaya et al., 2018; Nieto-

Lugilde et al., 2018), not proving assisted migrations recommendations. Additionally, many scientists just used abundance data (Waldock et al., 2022) and climate data to produce these predictions. This methodology overestimates species and ecosystem shifts especially for trees because mature trees can survive outside their climatic niche (Hogg, 1994) and the natural migration of trees is limited by seed availability, soil quality, and biotic interactions, not just climate. So, Real-world species and ecosystem shift being is much slower than climate based habitat suitability modeling. This resulted in a lot of well-deserved push back citing that this methodology disregarded dispersal, soil, phenotypic elasticity, and disturbance effects (Liu et al., 2009; Santini et al., 2021). This resulted in more complex models attempting to account for these external factors. For example, in Canada where wildfire plays a key role, researchers incorporated disturbance into their scenario to account for the plasticity of mature trees (Schneider et al., 2009). While there are limitations to the real-world migration prediction capabilities of habitat suitability modeling based on climate data, it is the tool to use for calculating climate adapted seed sources and species for assisted migration (Araújo and Peterson, 2012).

2.6 Habitat suitability modeling and assisted migration

Climate adapted seed sourcing recommendations do not need to provide a comprehensive realistic prediction of the effects of climate change on living trees. Seed sourcing recommendations are trying to simply determine what seed sources would be best adapted to the new climate and this justifies a simpler solution. In this case a simple climate site comparison (climate matching). That is not to say abiotic and biotic disturbances should not be considered in assisted migration experiments. In fact, the main criticism of papers in opposition to assisted migration is that soil and biotic factors are not considered in most assisted migration recommendations (Xu and Prescott, 2024). Instead, the question is whether that consideration should be addressed within the seed source modeling or with site specific silvicultural knowledge. The Xu and Prescott comprehensive 2024 review of assisted migration in forestry called for models that integrated non-climatic factors in assisted migration seed recommendation. Often soil data is left out of habitat suitability modeling due to lack of data and it can artificially shorten assisted migration distances resulting in poor climate matches. Additionally, what parts of the soil are important for what species vary. However, not including soil, leads to the assumption that the leading edge of a species' future climate niche has suitable soil which can cause overestimation of suitable habitat (Burns, 1990; Feng et al., 2020) and reduce the precision and efficacy of assisted migration strategies (Xu and Prescott, 2024). Park and Talbot (2018) suggest silvicultural knowledge can fill these gaps. For example, in Mexico integrating ectomycorrhizal fungal communities into their assisted migration experiments with Abies religiosa had promising results (Argüelles-Moyao and Garibay-Orijel, 2018). I predict a combined approach that utilizes the biotic and soil data widely available in North America to filter out climate matched seed sources but is not incorporated in calculating the climate matches themselves could be successful if data is widely available. However, overcomplicating models or including incomplete data can make the recommendations harder to interpret and in the worst case provide misleading recommendations. Further interdisciplinary research like the DIVERSE assisted migration trials is needed to determine if local silvicultural knowledge or more intricate modeling is called for to take habitat suitability modeling from species mapping to climate-informed tools that guide forest conservation, reforestation, and policy decisions in a warming world.

2.7 Habitat suitability modeling methodology

In the literature habitat suitability models are calculated by matching historic climate to projected climates under climate change (climate matching) or by developing trait-based models tying tree growth to climate variables (Xu and Prescott, 2024). The methodology used to develop these recommendations is quite different and they both have different strengths and weaknesses.

2.7.1 Trait-modeling recommendations

Trait modeling recommendations require extensive provenance trials of a species and different seed sources across an environmental gradient to model the growth response of a seed source to climate. For example, Ukrainetz et al. (2011) uses trait-based modeling to demonstrate that a focal point seed transfer system that simply calculates the growth reduction expected as seedlings are planted further from their source could reduce the seed collections needed and help implement more flexible assisted migration recommendations. Like most trait model-based recommendations this paper looked at a limited number of species, in this case three interior spruce species and their hybrids in British Columbia, because the development of these models requires provenance trials to model the relationship between tree growth and climate. Because this approach is at the species population level it doesn’t account for community biotic interactions and traditionally assumes no soil variation unless that is explicitly added (Buri et al., 2017; Feng et al., 2020; Xu and Prescott, 2024). Additionally, sometimes growth rate, the trait most models are attempting to optimize, isn't the most important trait and can increase risk especially in extreme climates. For example, in more extreme northern climates survival rate is of higher priority than growth rate (Burns, 1990). However, if developed it is a more flexible seed transfer system than fixed seed zones and climate niche recommendations, so it could be helpful in more remote areas with fewer seed lots (Ukrainetz et al., 2011).

2.7.2 Climatic matched recommendations

Climatic niche modeling uses historic climate data and distribution data to determine the climatic niche, and then, uses general circulation model's climate projections to map the climatic niche onto predicted future climates. This is similar to the methodology of a lot of the papers focused on predicting how climate change might impact species distribution because the data needed for this analysis is often publicly available (Wang et al., 2025). Additionally, it can be applied to all the tree species at once if species distribution or abundance data is available for the historic climate niches. Another strength is that the seed source recommendation location is not influenced by any biotic or soil interactions because traditionally only climate data is considered when calculating the climate matches. However, Species recommendations with this methodology are still affected by non-climate driven abundance factors, such as deforestation and soil types.

Trait and niche modeling approaches can be combined. Climate niche models can be used for seed sources and trait models can be utilized to assess the planting sites suitability for specific species. In general, Trait models can be too aggressive while climate niche recommendations are not supported by field experiments. A combined approach, when possible, can provide robust recommendations. However, due to the extensive field trials needed for trait models and the large scale of the DIVERSE project, with a diverse array of species, climate matching is more operationally feasible, so I focus more on climate matching for the rest of the review.

2.7.3 Climate niche scale

How the niches are defined is key to successful assisted migration recommendations. Ideally the recommendations should be at the population level. The population should be defined with the goal of minimizing genetic variation within the niche and maximizing genetic variation between each niche (Gray and Hamann, 2013; Hamann and Wang, 2006; O'Neill et al., 2017). Hamann et al. (2011) developed a seed transfer system using genetic variation and climate data to calculate the best seed zones for assisted migration. Specifically, they used latitude and elevation as a proxy for climate variation and created partitions where the most genetic variation could be explained by the climate proxy variables. They then use those values to inform seed zones for seed transfer guidelines. This must be done at the species level because it requires an extensive genetic data set for each species. So, while not feasible for the DIVERSE assisted migration experiments, it explicitly illustrates how assisted migration could help preserve genetic diversity and how important the climate niche delineations are for effective genetic conservation with assisted migration (Hamann et al., 2011). Additional research on genetic diversity and seed zones can always help confirm assisted migration recommendations are helping to preserve genetic diversity. However, minimizing genetic variation within the niche and maximizing genetic variation between each niche has been the goal of seed zones developed in the last century based on decades of provenance trials, observation and in some cases genetic testing. So, I argue that the current ecosystem delineations and seed zones are likely already a good proxy for genetic diversity and good scale to provide assisted migration seed transfer recommendations.

Researchers in British Columbia, after using a multiple criteria decision making framework came to the same conclusion and decided to build off of the current a current ecosystem zoning system in British Columbia, specifically the bio geoclimatic ecosystem classification (BEC) zones

("BEC Map," n.d.; O'Neill et al., 2017). In British Columbia the BEC zones were developed from observation (MacKinnon et al., 1992) and improved with the provenance trials of the Assisted Migration Adaptation Trial (AMAT) project, so they are particularly suited to assisted migration because they represent species response to different climates. However, The DIVERSE team is testing species outside their current ranges where there might not be seed zones. In this case ecosystem delineations are often the starting point for seed zone development and are the best available substitute (Linyucheva and Kindlmann, 2021).

It should be noted that climate niche matching can be done at the climate niche level, species level and at the rasterized pixel level. And that it has already been done for all north America at the ecosystem to pixel level (Rehfeldt et al., 2006), and on the west coast at the tree species ranges at the pixel to pixel level (Gray and Hamann, 2013) and in many more studies (Araújo and Peterson, 2012). However, these studies did not provide specific operational assisted migration recommendations. I chose to provide our recommendations at the geographically larger climate niche to climate niche level because that level is still genetically relevant and integrates with current seed sourcing and planting guidelines making it more operationally clear.

2.7.4 Climate matching algorithms

The scale of recommendations additionally influences the type of model used to match the historic climate to the new climate projections. Modelers have used random forest for rasterized ecosystem to pixel matching (Rehfeldt et al., 2012) and neural networks have even been suggested for climate change impact predictions (Beery et al., 2021; Gobeyn et al., 2019; Li and Wang, 2013). These machine learning regression models work great for pixel level predictions or ecosystem to pixel predictions because these algorithms consider all the climate data within the ecosystem and develop cutoffs for ecosystem classification or relationships between climate variables and species abundance (regression). However, assisted migration experiments usually involve testing multiple seed sources, the DIVERSE project is no exception. So, recommendations of multiple seed sources ranked by the quality of the climate match are needed and this is not something that can be done elegantly with a Neural network or a random forest model.

All of the current assisted migration tools mathematically compare climates instead of using machine leaning models, independent of the scale they provide predictions at (McKenney et al., 1999; O'Neill et al., 2017; St. Clair et al., 2022). Two of the tools determine the climate matches by calculating the Euclidean distance of multiple climate variables. The simplicity of the Euclidean climatic distance means it can easily be determined what climatic variables are farthest and closest to the current climate; while machine learning algorithms predictions are more of a black box with limited data on what led to the prediction, especially for neural networks. For a simple climate comparison at the larger ecosystem geographic the increased precision of machine learning modeling techniques would likely not impact recommendations and would add unnecessary complexity and computational demands. However, it should be noted that using the average normalized climate of an ecosystem to represent its climate, as is done when calculating the Euclidean climate distance, does disregard the climate ranges within ecosystems (Schneider, 2004). This goes back to how important it is that the recommendation delineations are relatively homogeneous zones.

2.8 Climate informed seed sourcing tools

This literature review found three seed sourcing tools that can be used for assisted migration (McKenney et al., 1999; O'Neill et al., 2017; St. Clair et al., 2022). The first one developed is a GIS tool that allows the user to compare historic and projected climate data anywhere where a digital elevation Model and interpolated climate data exists. The other tool that can be applied across Canada was developed at Oregon State by St. Clair et al. (2022). Both tools help users create raster maps indicating climate matched areas that could be viable seed sources for assisted migration. St. Clair et al. (2022) uses the climatic Euclidean distance while (McKenney et al., 1999) uses a grower metric equation. Both tools are designed to be used by forest managers for seed selection analysis. However, they both require background knowledge and expertise in climate modeling and seed selection. They are valuable decision support for experienced foresters focused on one species or site, but the fine scale of the rasterized recommendations makes them hard to use for recommendations at the seed lot level for multiple sites like is required for the 22 partner forest management areas in the DIVERSE project. Additionally, while both tools incorporate trait-model based species recommendations where possible, the diverse forest management areas need comprehensive species recommendations for all relevant tree species.

The last tool is a proposed assisted migration seed transfer system in British Columbia developed by O'Neill et al. (2017) that climate matches seed zone to seed zone using climate Euclidean distances and then layers species specific climate based transfer functions, developed from the AMAT work (O'Neill et al., 2013) to also provide estimates of tree growth for the suggested seed transfer. This approach is simple and easy to communicate. However, the southern seed zones will need seed sources from outside of British Columbia. So, as of 2021 they are calling for coordinated cross boarder seed transfer from Oregon and Washington (O'Neill and Gómez-Pineda, 2021). Our work on a continental scale can help with this cross boarder assisted migration in British Columbia. This methodology is easy to scale and operationally clear. Additionally with tree species abundance data currently in the seed zones, we can also provide comprehensive species recommendations. I intend to take this approach and scale it up to include all of North America to calculate species recommendations for all the DIVERSE forest management areas.

3 Materials & methods

I used projected and interpolated historic climate data, ecosystem delineations, and tree species data to calculate seed sources and species recommendations under climate change by matching ecosystem's historic climates to the projected future climate for each ecosystem in North America. All data analysis was done in the python programming language (Van Rossum and Drake Jr, 1995) using the following python packages (Gillies and others, 2013; Jordahl et al., 2020; team, 2020).

3.1 Ecosystem delineations

For this study, we selected the most widely used ecosystem delineations for different jurisdictions in North America. For the continuous US we used the level four ecoregions ("Level IV Ecoregions of the Conterminous United States," 2013) delineated by the methodology described in Omernik and Griffith (2014). For Alaska and Mexico, we had to use the less granular level three ecoregions (Omernik and Griffith, 2014) because it is what was available. For Alberta, we used level-4 seed zones because they are ecosystem based and not species specific ("NRC (2006) Natural regions and Subregions of Alberta," n.d.). For British Columbia, we selected version 6 of the Biogeoclimatic Ecological Classification (BEC) system for British Columbia ("BEC Map," n.d.), described in MacKinnon et al., (1992) so our work can integrate with their current climate-based seed transfer system (MacKinnon et al., 1992; O'Neill et al., 2017). For the rest of Canada, we used the terrestrial ecodistricts (Marshall et al., 1996; "Terrestrial Ecodistricts of Canada," 2013). This resulted in a combined 2201 ecosystem delineations of all of North America (Figure 2 left panel).

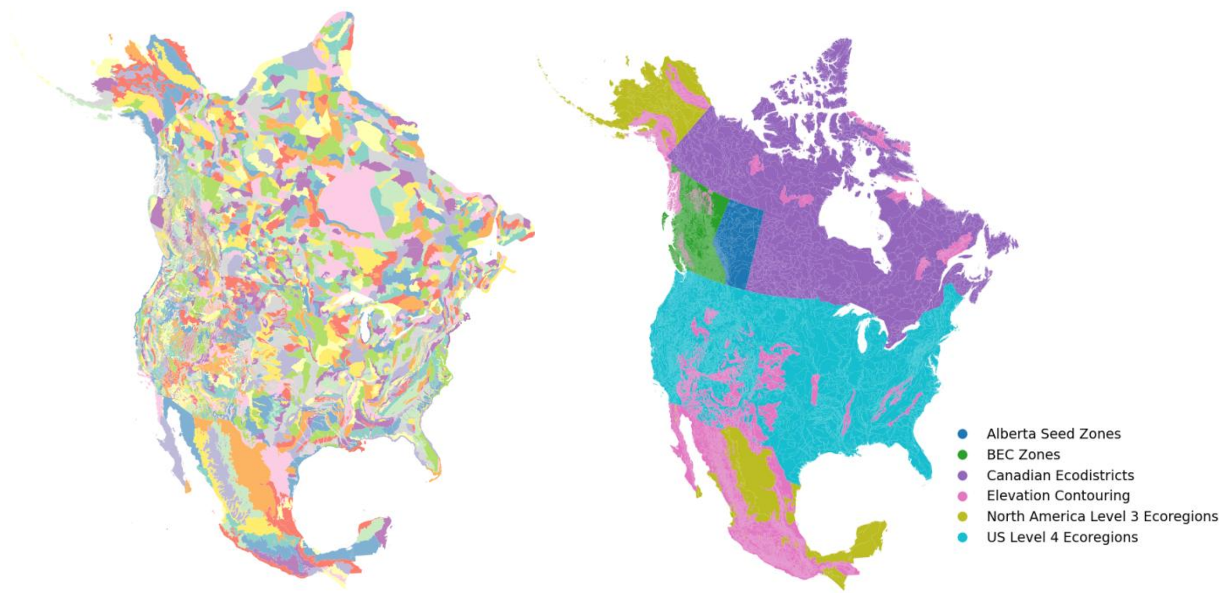


Figure 2. (left) Map of ecosystem polygons at the finest hierarchical level available. Note that the finest available level of ecosystem delineations in Alaska and Mexico are still quite large and do not track elevation as well as in British Columbia or the lower western United States (right) map of ecosystems after additional elevation contouring in pink colored by data source

Because some ecosystem delineations in mountainous areas were too broad to capture climatic gradients, especially in Alaska and Mexico, I added elevation bands to divide the larger ecosystems into more homogenous climatic delineations (Figure 2 right panel). Specifically, I subdivided ecosystems that had a Mean Annual Temperature (MAT) range greater than 4°C and had a Pearson correlation coefficient of at least -0.7 between elevation and MAT for individual grid cells that fell inside the ecosystem. These two criteria identified ecosystems with a large climatic range of climate values that could be removed by introducing elevation bands. Using the linear relationship between MAT and elevation, I calculated what change in elevation should result in a 2-degree Celsius change in MAT, reflecting environmental lapse rates that can vary between different general regions. Then, I divided the rasterized ecosystems along the calculated elevation bands, if the split resulted in an ecosystem of at least 1,500 km². The minimum size of 1,500 km² was meant to only delineate ecosystems of relevant size for management applications, and to ignore small, fragmented climate regions (e.g. mountain peaks), which were combined with the adjacent elevation band. This additional subdivision of some ecosystems with elevation bands raised the total number of ecosystem delineations from 2201 to 2270 for all North America.

3.2 Climate data

Climate data was generated for a subsample of ~800,000 1km resolution grid cells to represent the 2270 ecoregions, using the software version ClimateNA v6.40b that contains historical ERA5 anomaly data, available at http://tinyurl.com/ClimateNA, based on methodology described in Wang et al., (2016). To represent the ecosystem's climate conditions, I used 11 biologically relevant climate variables, also referred to as bioclimatic variables (Burns, 1990): Mean Annual Temperature (MAT), Mean Warmest Month Temperature (MWMT), Mean Coldest Month Temperature (MCMT), Temperature Difference (TD) or continentality, calculated as MWMT – MCMT, Extreme Minimum Temperature expected over a 30-year period (EMT), Mean Annual Precipitation (MAP), May to September growing season precipitation (MSP), Precipitation As Snow (PAS), Climate Moisture Index (CMI), Growing degree days above 5°C (DD5), Chilling

Degree Days below 0°C, and Number of Frost Free Days (NFFD). Mountain climates can be significantly more variable, with a much higher probability of late spring frosts or early fall frosts, given the same mean annual temperature values as in low elevations or plains, so we also included elevation as a variable in the climate matching calculations so the recommendations favor the movement of seed sources northward along similar elevations within mountain ranges instead of the riskier upward in elevation recommendations.

For our predicted future climate data, we chose an ensemble of 8-general circulation models from the Coupled Model Intercomparison Project Phase 6 (Eyring et al., 2016; Mahony et al., 2022) selected by Mahony et al. (2022), consistent with the IPCC's recent assessment of the *very likely* range of Earth's equilibrium climate sensitivity (Arias et al., 2021). The ClimateNA software was used to calculate the selected bioclimatic variables under climate projections for the 2020s (2011–2030), 2050s (2031–2070) and 2080s (2071–2100) for a "middle of the road" greenhouse gas emissions scenario (social shared pathway 245). Historic climate periods were calculated for the 1960s (1951–1980) and 1990s (1981-2010), so that the main climate dataset for species habitat modeling consisted of five consecutive 30-year climate normal periods, with the first period 1951–1980 used as the reference climate the tree species populations are adapted to.

For additional visualization of climate change trends at target sites, decadal climate averages of interpolated weather stations data from the 1950s (1951-1960), through to the last complete decade 2010 (2011-1920), plus an incomplete estimate for the 2020s (2021-24 average) were also generated with the same software (Wang et al., 2016).

3.3 Climate matching

For climate matching, the Euclidean distance of each ecosystem's average climate was used because it is simple, transparent and effective. This is similar to the approach taken in British Columbia (O'Neill et al., 2017). To prepare the climate data (1960s, 1990s, 2020s, 2050s, and 2080s) for calculating the Euclidean distances I first normalized the skewed variables log(MAP+10), log(MSP+15), log(CMD+30), log(DD_0+50), log(DD5+700), log(NFFD+400), log(PAS+10), sign(CMI) * log(abs(CMI)+1) with MAT, MWMT, MCMT, and TD remaining untransformed. To give each variable the same weight, I scaled all the climate data together (historic and projected) so that scaled Euclidean distances from different time periods were comparable by subtracting the combined mean and dividing by the combined standard deviation.

3.4 Expected forest cover

The expected percent of forest cover for each ecosystem was partially derived from the MODIS vegetation continuous fields (VCF) MOD44B Version 6 (DiMiceli et al., 2021). I converted the raster to the LCC projection and aggregated the data to a 1km resolution, with an average of 10,516 data points per ecosystem and a minimum of 492 data points per ecosystem. Mean VCF values by ecosystems are shown in Figure 3 (left panel).

In order to scale expected species frequencies to sum up to the expected forest cover of an ecosystem, we carried out an additional adjustment for forest cover lost due to human development based on data provided by Zimmerman et. al (2025). Briefly, MODIS land cover classification data (Commission for Environmental Cooperation. (2013)., n.d.) was used as a dependent class variable to train a deep neural network, except agriculture and urban classes were omitted from the training process. Predictor variables used included 14 climate and 12 topographic variables, and the model was then applied to the same variables for the same area, replacing agriculture and urban classes with the landcover class (other than agriculture and urban) that had the highest probability according to the neural network. Area classified as water was excluded from both training and prediction. The proportion of the forest cover backfilled by the neural network was then used to estimate a new expected forest cover (Figure 3, right panel)(Zimmerman et al., 2025). Subsequently, the backfilled forest cover was used to scale expected species frequencies to sum up to the backfilled forest cover percentages for each ecosystem, so climate was more of a driver of species frequencies than human caused deforestation.

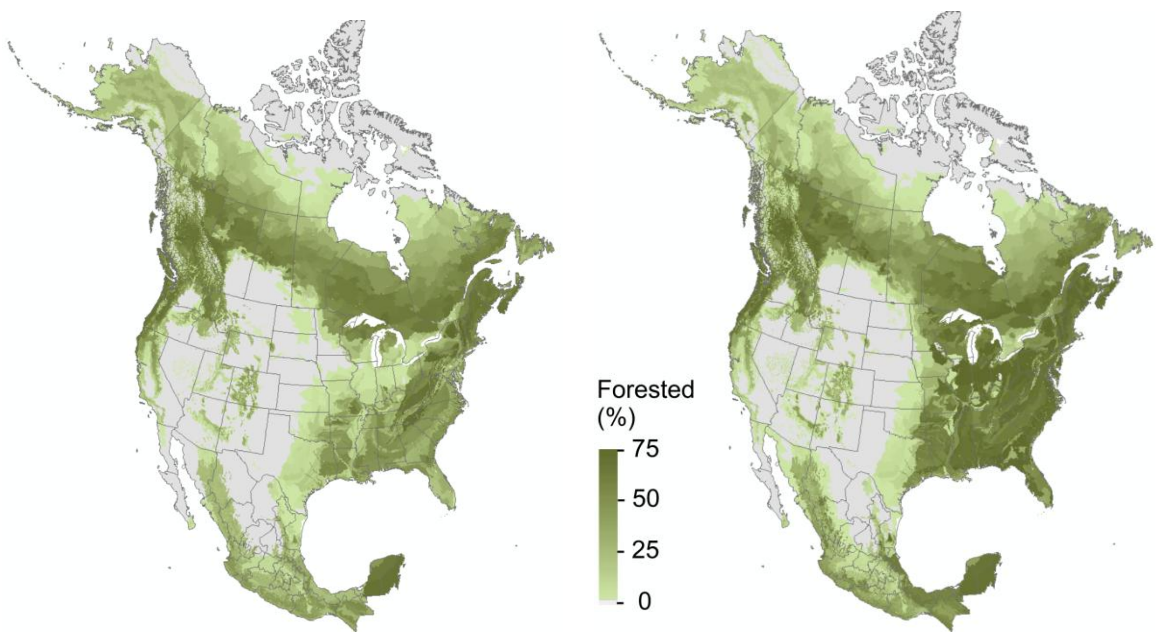


Figure 3. (right) Ecosystem averages of forest coverage based on MODIS vegetation continuous field data (left), and with agricultural and urban areas back-filled according to the most probable land cover class.

3.5 Tree species data

I inferred tree species compositions for the ecosystems in Alaska using the National US forest inventory plots (Gray et al., 2012; "National Forest Inventory," n.d.) data collection and management methodology described in Gray et al., (2012). I first calculated the average basal area of all the species in each plot by summing up the basal area of each tree species per plot for every year that the plot was measured and then took the average basal area per species across all the years the plot was measured. I then used the provided plot latitude and longitude data to calculate which ecosystem the plot was in. I used a minimum of 25 plots per forested ecosystem. I considered ecosystems that were at least 30% forested as forested ecosystems. If the forested ecosystem did not have enough plots inside it, I used the 25 closet plots. I then took the averaged total species basal area of each species across all the plots within or near each ecosystem and used that as a proxy for the species percentages within the ecosystems. It should be noted that the US Forest Service plot latitude and longitude data is not exact to protect the privacy of landowners. However, the ecosystems are big enough that exact plot locations were not necessary.

For Canada (Beaudoin et al., 2018) and the contiguous 48 lower US states (Wilson et al., 2012) we used two 250 m resolution raster datasets that were generated by training a k nearest neighbor algorithm on the Canadian and US national forest inventory plots to classify species composition when given MODIS spectral data as input. To summarize the species composition by ecosystem, I used the centroid for each pixel in the rasters to determine which ecosystem it was in and then averaged of the pixel's percent species compositions by ecosystem.

For a consistent species nomenclature, I merged the Canadian and US data using the Latin names and common names wherever that was unambiguously possible and I added the Little's (1971) species codes because it is the same nomenclature used for the Silvics of North America (Burns, 1990), which is a widely used reference by forestry practitioners.

3.6 Species recommendations

Using the expected forest cover and the species composition data I scaled individual expected species frequencies for each ecosystem by the expected forest cover data, so that species' frequencies of all species + expected non-forested = 100% of the ecosystem land base. To infer the suitability of species habitat for the climate periods, I used the average species frequency from the five closest climatic matches. Using an average of five closest climate matches, mitigates some erratic changes that could arise from poor species frequency estimates for a single ecosystem due to sparse forest inventory data or an unusual species composition due to unique soil conditions or other topoedaphic factors in a single ecosystem.

3.7 DIVERSE forest management area summaries and seed sourcing tool

Participants of the DIVERSE project are planning assisted migration experiments for 22 forest management areas across Canada (Figure 1). To summarize recommendations for the 22 forest management areas, I calculated area-weighted averages of expected species habitat for the two historic climate normal periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). These summaries are meant to show which species will be relevant in the future for forest management in each forest management area. The same data is also reported by the geographically smaller ecosystems within each forest management area because forest management area can in some cases span substantial climatic gradients. To communicate all this data we developed an on-line webtool (http://tinyurl.com/DIVERSE-SST), meant to select species and seed sources for a particular planting sites within a forest management area. The web tool was developed using the leaflet r library (Cheng et al., 2025; R Core Team, 2021). It first allows users to select a province, forest management area, ecoregion and then eco district for which they would like to obtain a recommendation (Figure 4). Once selected, the tool displays the graph of the ecosystem's climate's change over time, corresponding species habitat for the 1960s, 1990s, 2020s, 2050s and 2080s and allows the user to filter by ecosystems of Canada and the United States as potential source locations for planting stock.

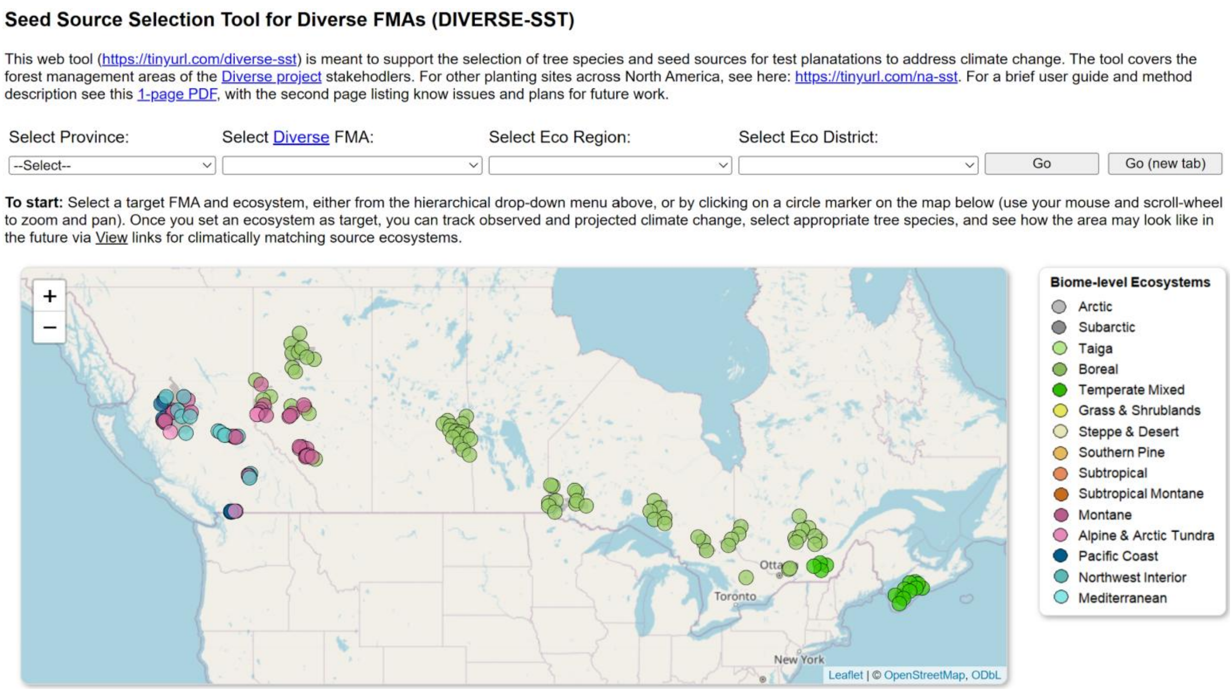


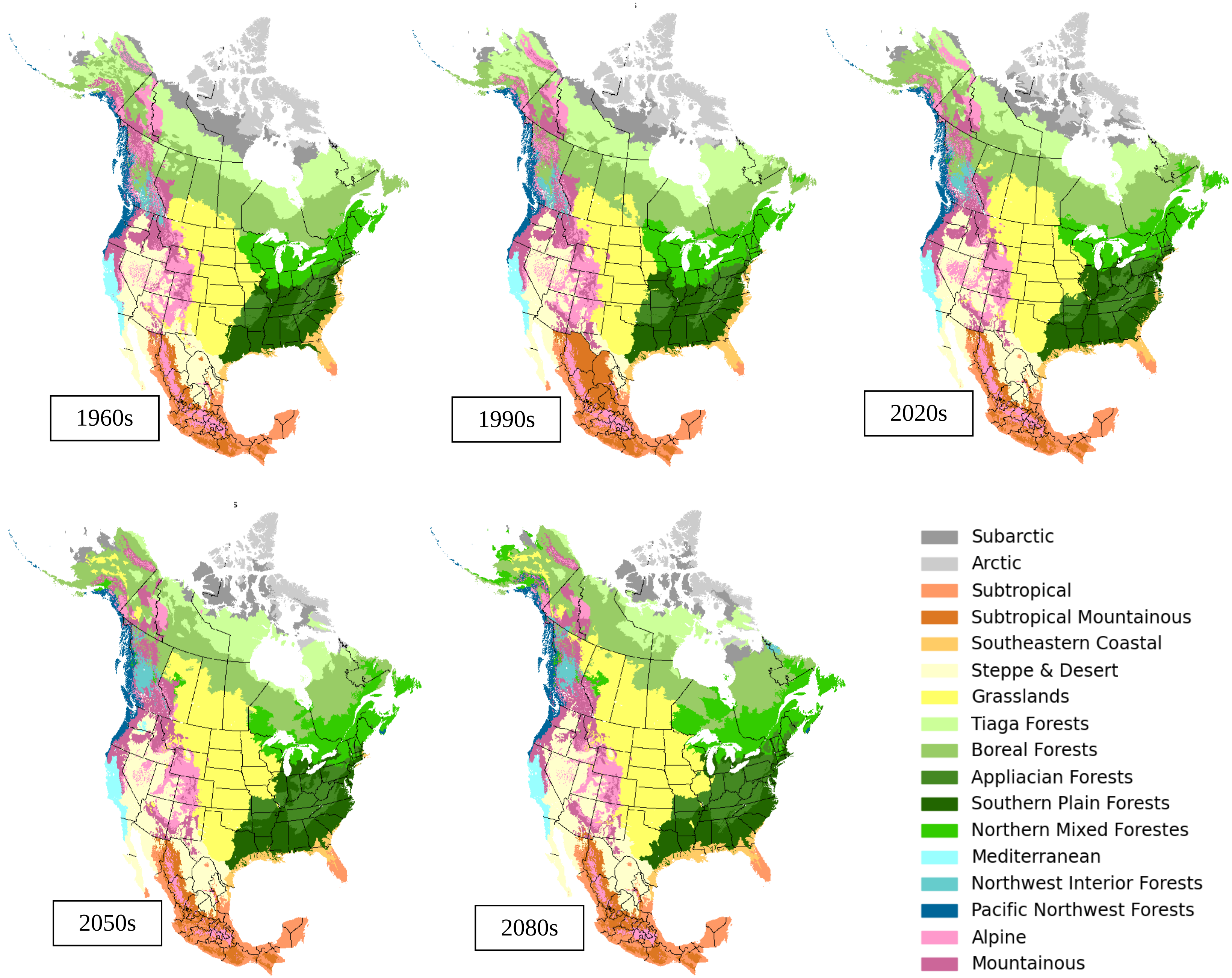
Figure 4. Home page of the online seed source selection tool. Each dot represents one ecosystem within the 22 DIVERSE forest management, colored by biome according to the legend to the right.

4 Results and Discussion

The DIVERSE assisted migration recommendations are based on ecosystem to ecosystem climate matches. Figure 5 displays the climate matches behind the recommendations through higher-level summaries of the climate matches' biomes and expected forest cover, assuming no human development. The forest cover implies where the climate matches will be operationally relevant (e.g. whether or not there are trees for seed souring in those climate matches).

The climate matched biome maps are similar to a previous model developed by (Rehfeldt et al., 2012) that used the more complex random forest model and climate matched at a finer scale. From a management perspective the northward shift of the grassland biome climate and the decrease in forested climate matches in Alberta while consistent with other researchers' findings (Rehfeldt et al., 2012; Schneider et al., 2009) complicates assisted migration recommendations for these forested areas and is explored further with more specific examples later in the discussion.

The 2020s climate matched biomes show a general northward shift which is continued in the 2050s and 2080s with some exceptions. Climates suitable for grassland biomes generally expand northward into the western boreal forest regions and even appear in Alaska by the 2080s. Other long-distance climate matches occur between the northeastern mixed forest biome and the Alberta foothills and coastal Alaska by the 2080s. This was also found by Rehfeldt et al. (2012), so multiple methodologies concur with respect to general climate matching patterns across the continent.


1960s
1990s
2020s
2050s
2080s
Subarctic
Arctic
Subtropical
Subtropical Mountainous
Southeastern Coastal
Steppe & Desert
Grasslands
Tiaga Forests
Boreal Forests
Appliacian Forests
Southern Plain Forests
Northern Mixed Forestes
Mediterranean
Northwest Interior Forests
Pacific Northwest Forests
Alpine
Mountainous

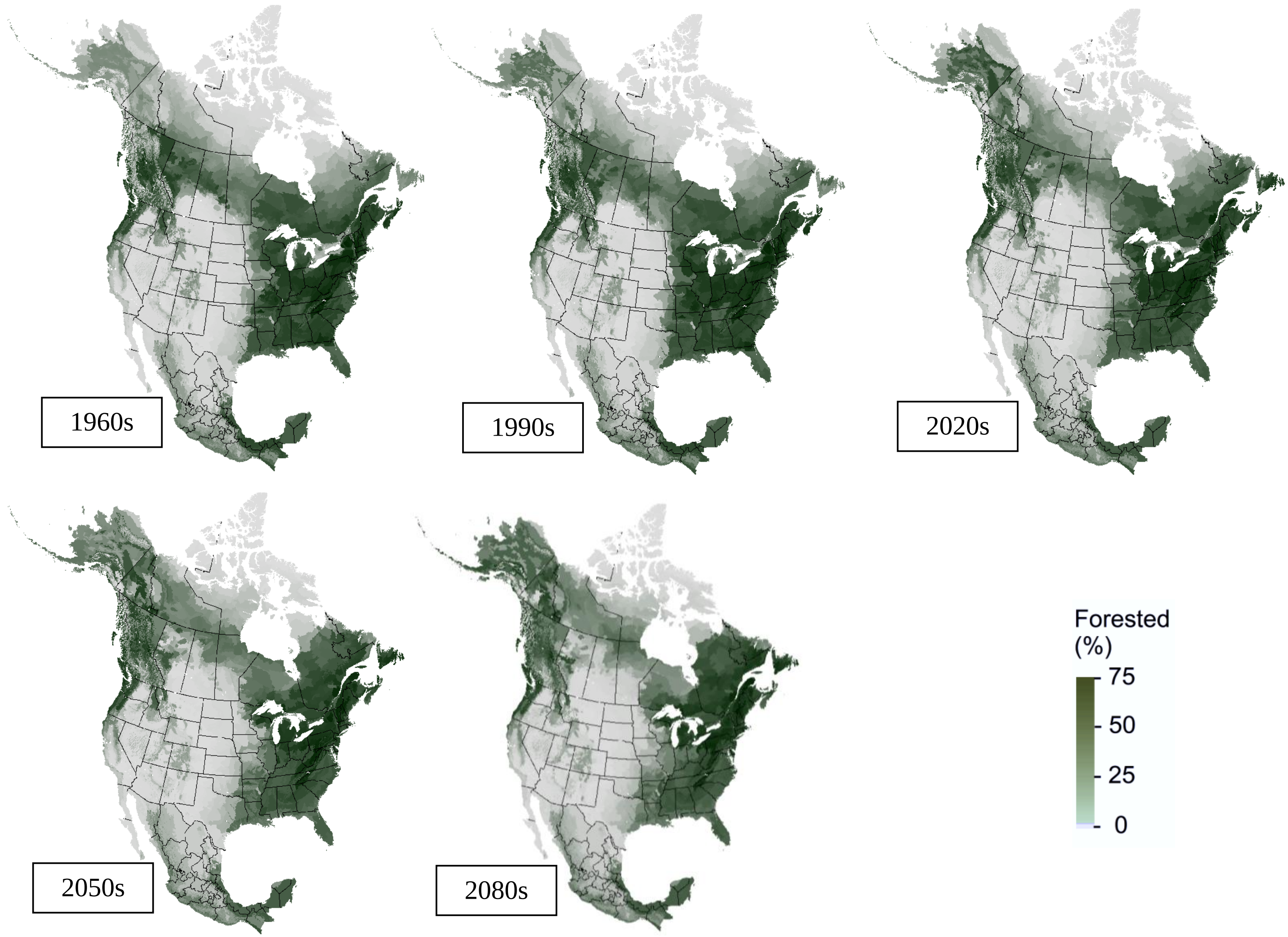


Figure 5. Climatic habitat supportive of different biomes (top panel) and forest cover assuming no human development (bottom panel) for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). The predictions are based on a majority vote of biome types or average forest cover from the 5 best matching level-4 ecosystems

When interpreting Figure 5 it is important to keep in mind that the purpose of Figure 5 is to summarize the climate matching and species data behind the DIVERSE assisted migration recommendations. The graph should not be interpreted as a prediction of how species composition and forest cover will actually change throughout this time frame. Actual changes to ecosystem composition with long-lived species like trees takes place over much longer time frames. That said, the shifts in suitable climate habitat can be interpreted as species communities being potentially in equilibrium in those climate conditions, and maladaptation due to these shifts in climate conditions can manifest through reduced growth potential and increased tree mortality (Liu et al., 2023).

4.1 Summaries across forest management area

The analysis of maintenance of species habitat on the forest management areas of the 22 Diverse partners shows that for the majority of the holdings forest cover (expressed as the sum of expected individual species frequencies) is maintained from the 1960s through the 2080s (Figure 6). There are exceptions, however, where the expected forest cover is predicted to decline to less than 20%, namely for Paquia Porcupine and Peace River East, with it also declining in Kamloops, Sundre and Grande Prairie. These are forest management areas positioned in already dry ecosystem types of the boreal forest, either in the dry mixed woods of Alberta or near the southern fringe of the boreal forest, not far from the transition zone to grasslands, and which are predicted to have reduced climate habitat for forested ecosystems in the future (c.f., Figure 4).

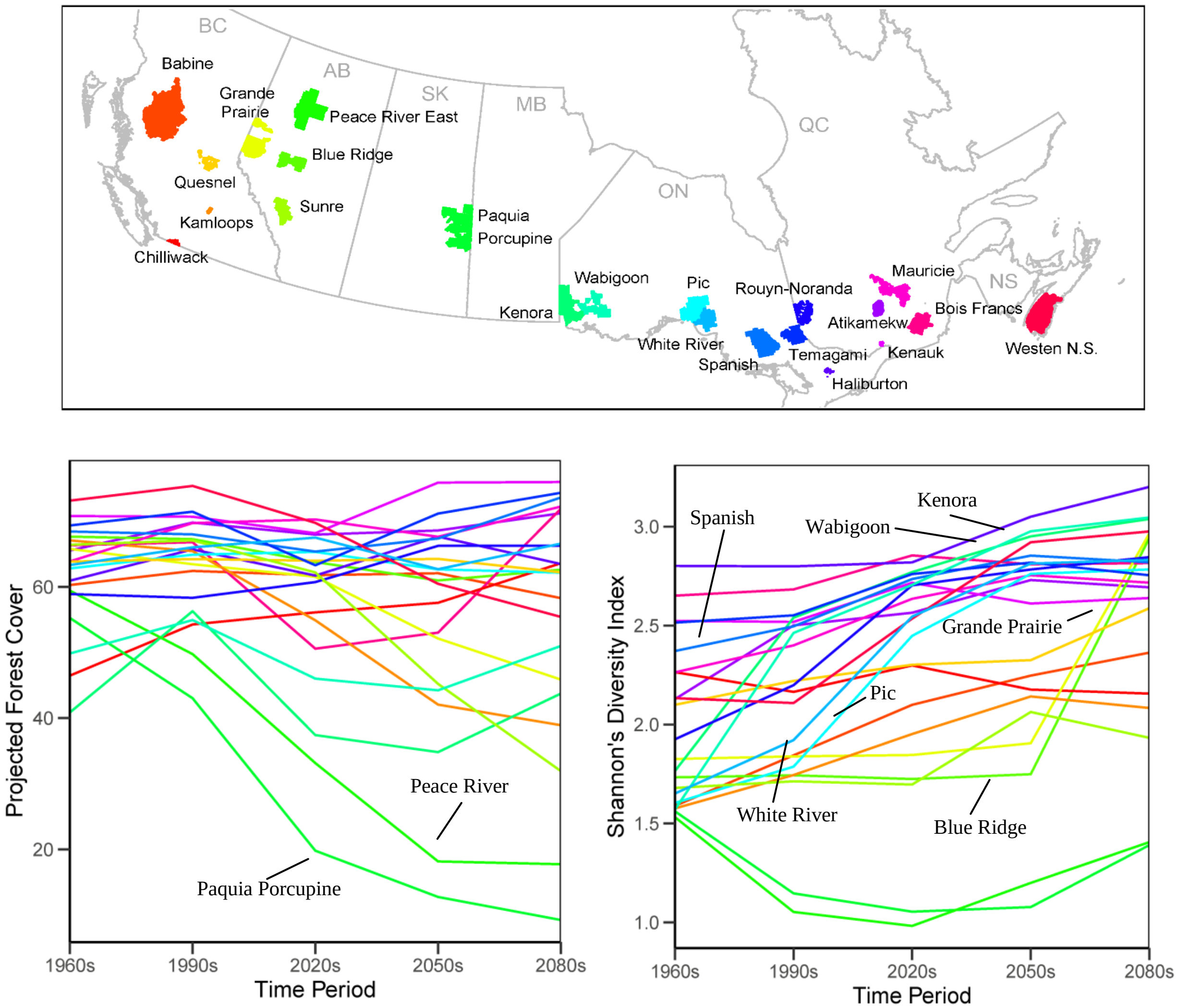


Figure 6. Maintenance of climatic habitat for forest tree species, summarized for 22 forest management areas of DIVERSE project participants (upper panel). The line plots show the sum of historic and future climate habitat (lower left), and the diversity of potential tree species habitat (lower right).

In terms of tree species diversity, almost all forest management areas are predicted to maintain or increase the diversity potential of tree species habitat, albeit at a lower level for the central Canadian forest management areas (green shades). The largest increases in diversity potential tree species habitat are expected for central-east forest management areas (Wabigoon, Pic, White River, Spanish, Kenora), where suitable habitat for new species due to historical climate change trends has already emerged in the in the 1990s as well as for current climatic conditions (2020s).

Projections of higher diversity of potential tree species habitat also emerged in the 2080s climate matches for forest management areas in the foothills of Alberta (Blue Ridge and Grande Prairie). However, this is due to climate matches in northeastern mixed forests (Figure 6) that would be risky to utilize as seed sources in assisted migration, because it would require transcontinental migration. Therefore, that increase in diversity is not likely to be realized because it could not occur through natural migration and it is not recommended from a management perspective.

The increase in diversity of potential tree species habitat is driven by the northward expansion of climatically suitable habitat of tree species that primarily (or only) occur in the US. This implies an opportunity for Canadian forestry operators to expand their species portfolio and create more diverse forest ecosystems with species that under observed and projected climate change could find suitable habitat conditions in Canada. This increase of diversity through introduced species could also lead to greater overall functional resilience of forest ecosystems, potentially serving as a hedge against uncertainty in climate change.

A technical limitation of this analysis is that we potentially have a confounding factor due to the combination of separate forest inventory sources from the United States and Canada. The US forest inventory contains more tree species, including minor species, whereas the Canadian database focuses on major tree species. However, this potential issue was addressed by removing all tree species that were not classified as a “Major tree” from the US database, and by using the Shannon’s diversity index that is less driven by species richness but also requires evenness of species frequencies for a high index value. Thus, increases in Shannon’s diversity (Figure 6) are mostly driven by new species climate habitat becoming available for major tree species.

The two forest management areas in central Canada where the analysis implies a significant loss of forest tree species habitat (Paquia Porcupine, Peace River East) is caused by these holdings becoming too dry to support forest tree species under projected climate change. The same applies to a lesser degree to Kamloops and Sundre. This result is consistent with other researchers' findings (Rehfeldt et al., 2012; Schneider et al., 2009) and Figure 5 that illustrates that dry mixed wood ecosystems in Alberta will be replaced by climatic habitat more suitable for grasslands in the future. These forest management areas are not likely to be good candidates for commercial forestry operations in the future but may become more suitable for other land uses (e.g. agriculture, rangelands) if soil conditions are appropriate.

4.2 Future species importance for forest management areas

To communicate to stakeholders what species could be relevant for assisted migration in their forest management area, I calculated area-weighted averages of species habitat across the ecosystems within each forest management area. Table 1 is an abbreviated example for the Peace East River Forest management area in Alberta. Full tables are available for all forest management areas in the Appendix.

The Peace River East forest management area is one of the central forest management areas that is expected to lose a large portion of climatic habitat that is suitable to support tree species (Table 1). Future climate conditions are projected to be similar to historic conditions that have been largely converted to croplands and range lands. If soil conditions allow, the Peace River East forest management area is projected to be more suitable for agriculture uses (likely range land) than for commercial forestry operations. Suitable species habitat for all tree species is predicted to decline, although quaking aspen appears to remain a relevant forestry species and could likely be maintained as a commercial forest tree in the future.

Table 1. Modeled climatic habitat of species for the Peace River East forest management area. Projections are for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). The values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems. The table is for illustration and does not include all species. For the complete table refer to the Appendix A13.

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non forested	45.957	68.983	74.992	87.186	86.387
	Cropland	13.727	49.871	50.596	63.048	61.607
Populus tremuloides	quaking aspen	22.282	21.103	17.75	8.635	8.291
Picea mariana	black spruce	14.142	3.252	2.525	0.522	0.432
Picea glauca	white spruce	6.216	2.46	1.551	0.373	0.265
Pinus banksiana	jack pine	4.837	0.658	0.549	0.23	0.224
Larix laricina	tamarack	2.815	0.56	0.823	0.153	0.188
Populus balsamifera	balsam poplar	1.762	1.639	1.283	0.521	0.454
Pinus contorta	lodgepole pine	0.526	0.628	0.052	0.001	0.001
Betula papyrifera	paper birch	0.506	0.26	0.218	0.234	0.311
Abies balsamea	balsam fir	0.079	0.025	0.055	0.247	0.299
Thuja occidentalis	northern white cedar	0	0	0.005	0.119	0.199
Fraxinus nigra	black ash	0	0	0.004	0.141	0.245
Fraxinus pennsylvanica	green ash	0	0	0.001	0.359	0.534

Although the loss of suitable forest climate in Alberta (predicted in Figure 4, and (Rehfeldt et al., 2012; Schneider et al., 2009)) is severe in the Peace River East area (Table 1), the current populations there are still a conservation concern. The combination of loss of forest habitat in general and rapid loss of habitat for a specific species like lodgepole pine could indicate a rear edge effect (Hampe and Petit, 2005), meaning those lodgepole pines could be a population adapted to the rear southern edge of lodgepole pine's climatic range, and it could have adaptations and genetic diversity that are especially important to preserve for usage elsewhere in assisted migration. Thus, seed collections by the Peace River East operators will potentially have high value for deployment in other regions that in the future will have climates similar to Peace River East's historic climate.

When interpreting the summary Tables of the forest management areas it is important to remember the corresponding appendices are weighted averages across different ecosystems in the forest management area. Therefore, the summary tables are not specific enough to directly guide the establishment of test plantations in larger forest management areas like Peace River. Recommendations should be given at the geographically smaller ecosystem level within each forest management area.

4.3 Species recommendations at the ecosystem level

However, there are hundreds of ecosystems in Canada so to communicate the species recommendations at the ecosystem level an on-line web application was created (Figure 4), accessible at http://tinyurl.com/DIVERSE-SST. In the next sections the results displayed by the tool for two contrasting ecosystems (Figure 7) are analyzed as examples of how to interpret recommendations communicated by the tool. In Figure 7 the lower foothills 1.3 ecosystem on the left encompasses the majority of the eastern side of the Blue Ridge forest management area while Algonquin is the only ecosystem in the smaller Haliburton forest management area.

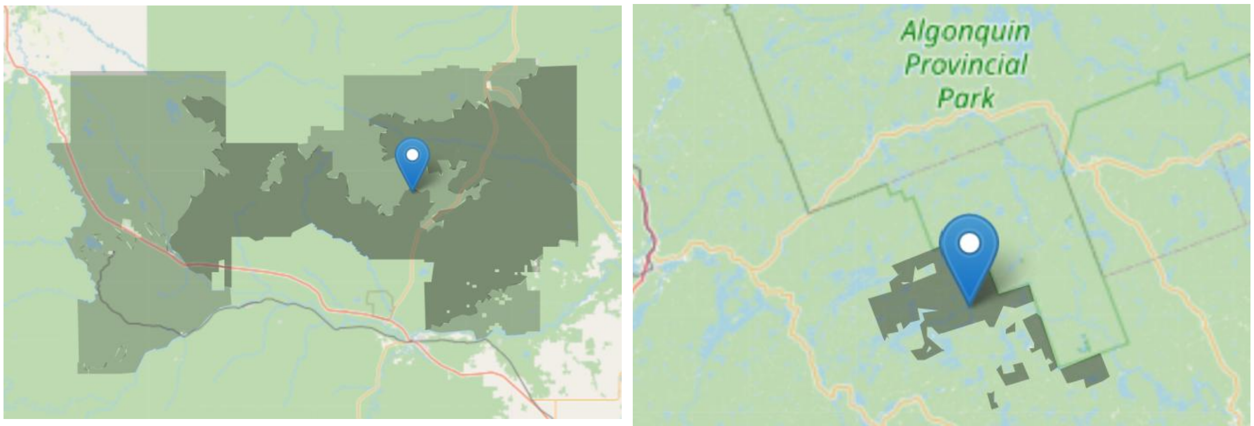


Figure 7. The lower foothills 1.3 ecosystem (left) and Algonquin ecosystem (right) Light grey shading indicates the forest management area outline and dark grey shading indicates the ecosystem.

4.3.1 Climatic analysis for ecosystems

The need for assisted migrations ultimately depends on the magnitude of observed climate change so the assessment process starts with an analysis of observed climate change compared to the projections. Once an ecosystem within a forest management area has been chosen in the web-tool, the first plot shows observed versus projected climate change. Figure 8 is the climate analysis graphs of the two selected example ecosystems, the lower foothills 1.3 in Blue Ridge and Algonquin in Haliburton (Figure 7). The solid arrows with black markers represent observed climate change in consecutive decadal time steps, and the dashed arrows with gray markers represent consecutive 30-year climate normal averages. The 1960 and 1990 normal periods are averages from weather station observations, but the 2020s, 2050s and 2080s represent multi-model future projections. Decadal precipitation time steps are more variable in general while the 30-year normals flatten out variability and show directional climate change. A key result to note in the climate analysis graphs is if the 1990s climate average is already outside the ecosystem envelope, like it is in the lower foot hills 1.3 (Figure 8 right) this indicates rapid realized not just projected climate change and the need for management intervention.

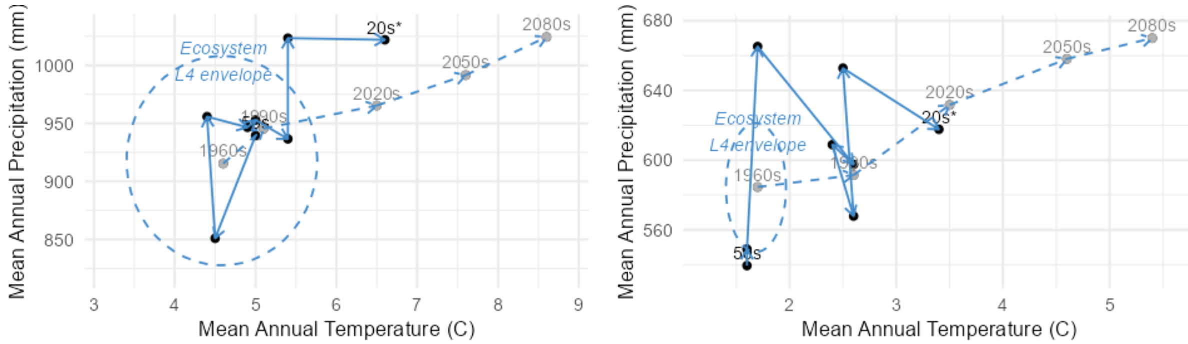


Figure 8. Climate analysis for the Haliburton ecosystem Algonquin (left) and the Blue Ridge Lower foothills 1.3 ecosystem (right). The solid black markers are decadal climate averages from the 1950s to present, observed at weather stations (50s = 1951-1960, ..., 20s* = 2021-2024) and the solid arrows connect these observed averages sequentially. Consecutive 30-year normal periods (1960s and 1990s) and the three projected normals (2020s, 2050s, 2080s) are the grey dots and they are connected with dashed arrows. The dashed circle is the ecosystem envelope (10^{th} to 90^{th} percentile).

In both cases (Figure 8), the magnitude and direction of observed and projected climate change approximately align, meaning selecting species and seed sources with the web tool should be a viable climate change adaptation strategy. That said, if historic climate change (historic decades 1950s to 2020s) significantly departs from future projections, then any species or population recommendations should be viewed with caution. Ultimately, we need to adapt to actual climate change, not the projections. If climate warms faster (or slower) than projected, then operators may plant for conditions further ahead in time (or less so). Further, increased precipitation can compensate for increases in temperature in terms of viable species choices. So, if historic climate change indicates that the site got drier than predicted, then an operator may compensate by planting for conditions further ahead in time (or vice versa). Additionally, precipitation is one of the hardest climate variables to predict accurately (Schaller et al., 2011), so the graph also allows the user to verify the precipitation projection.

Lastly it is important to note that while the climate analysis graph only displays mean annual precipitation over mean annual temperature for user assessment of observed versus predicted climate change, the tool itself calculates climate matched species and seed sources using multiple bioclimatic variables and elevation.

4.3.2 Loss or emergence of species habitat in ecosystems

If observed and projected climate change align, then the next step is selecting suitable species for assisted migration and verifying that the climate matched ecosystems are forested. Determining what species will likely have a future under projected climate change requires analysis of a species favorable climate over time. Table 2 and Table 3 are abbreviated examples of the downloadable tables of species frequencies overtime for the two example ecosystems, the Algonquin ecosystem in the Haliburton forest management area, and the Lower foothills 1.3 ecosystem in the Blue Ridge forest management area. These tables are available for all DIVERSE ecosystems via the web tool.

When interpreting these tables, it is important to remember that they are not predictions but a tool to communicate to the user what can grow in the projected climates overtime to help with species selection. An observed real-world increase in species prevalence is dependent on seed availability, soil, and competitors, all things intentionally not considered in this climate focused analysis. Inversely, established trees tend to have incredibly wide climatic tolerances (their fundamental niche) (Bonan and Sirois, 1992; Hogg, 1994) so mortality in real world populations due to maladaptation caused by climate change also lags behind climate-based distribution models. These tables are designed for seed sourcing not to predict real world shifts in species occurrence.

Table 2. Species selection table for Algonquin within the Halliburton forest management area. The values are the average of the 5 closest climate matches for each time period, and all the values are in % area of the ecosystem. Non-forested area is rescaled to remove human disturbance. The species' prevalences are scaled by non-forested area

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	39.07	34.29	38.29	32.35	36.52
	Agriculture	4.69	4.61	20.82	36.55	76.3
Acer saccharum	sugar maple	10.75	7.72	6.76	6.38	3.09
Pinus strobus	eastern white pine	5.07	7.8	7.05	5.18	1.72
Betula papyrifera	paper birch	4.59	4.05	1.39	0.48	0.16
Acer rubrum	red maple	4.54	6.84	8.94	9.35	5.21
Abies balsamea	balsam fir	4.25	4.14	1.79	0.3	0.03
Betula alleghaniensis	yellow birch	3.4	3.04	1.75	0.96	0.23
Tsuga canadensis	eastern hemlock	3.18	6.03	6.57	4.23	0.59
Thuja occidentalis	northern white cedar	2.87	1.68	1.95	1.52	0.55
Quercus rubra	northern red oak	2.43	3.14	2.89	3.63	3.27
Populus tremuloides	quaking aspen	2.06	0.98	1.31	2.08	1.12
Picea glauca	white spruce	1.7	1.03	0.32	0.18	0.48
Picea mariana	black spruce	1.42	0.93	0.06	0.02	0.01
Fagus grandifolia	American beech	1.4	3.06	2.62	1.9	0.61
Populus grandidentata	bigtooth aspen	0.84	0.56	0.62	1.42	0.66
Tilia americana	American basswood	0.82	0.32	0.83	1.74	1.96
Pinus banksiana	jack pine	0.81	0.69	0.04	0.5	0.69
Pinus resinosa	red pine	0.76	0.7	0.67	2.52	1.3
Fraxinus americana	white ash	0.72	1.58	3.28	3.6	1.92
Picea rubens	red spruce	0.71	2.11	1.17	0.12	0.01
Fraxinus nigra	black ash	0.63	0.34	0.44	0.62	0.51
Acer saccharinum	silver maple	0.56	0.52	0.1	0.56	2.13
Larix laricina	tamarack	0.43	0.35	0.14	0.15	0.23
Prunus serotina	black cherry	0.43	1.02	2.21	3.13	4.43
Populus balsamifera	balsam poplar	0.11	0.06	0.06	0.05	0.01
Ulmus americana	American elm	0.11	0.15	0.7	1.38	2.73
Quercus alba	white oak	0.08	0.11	0.36	2.56	3.52
Fraxinus pennsylvanica	green ash	0.06	0.04	0.21	1.43	3.75

When looking for suitable species for assisted migration the first step is verifying that the assisted migration seed sources are forested so there will be populations to use as seed sources. Both example ecosystem's expected forest cover (Table 2 and Table 3) remains relatively consistent. However, Algonquin's agricultural area in it 2080s is also high (76.3%). This is because Algonquins climate matches are heavily developed. This highlights why it is important to control for human disturbance, so the species' frequencies more closely represent their occurrence in that climate. It also highlights the assisted migration has its limitations. Forested and locally adapted seed sources are still necessary for assisted migration and climate adaptation. This is not possible if the climate matches are deforested by human development and could be an issue for Haliburton. That is why preserving genetic diversity and reducing deforestation is still so important for climate adaptation and conservation.

When looking at the species frequencies it is important to keep in mind what type of assisted migration you plan to implement. The least risky type of assisted migration is planting the same species but using a better climate adapted seed source this is referred to as population assisted migration and should be prioritized. Population assisted migration is possible when a species retains its relative abundance over time, like sugar maple, norther red oak, red maple, and eastern white pine in Table 2. In Algonquin all these species are good candidates for population assisted migration, especially as the climate of the ecosystem shifts outside of its historic envelope (Figure 8) in the 2020s climate projection.

Assisted migration experiments can also include range expansion which involves introducing new species when that species appears in seed source recommendations and its prevalence increases over time. In Algonquin (Table 2) the climate becomes increasingly favorable to black cherry, American elm, white oak, and green ash over time, possibly indicating a range expansion northward. However, assisted range expansion is riskier than population migration. The recommendations only consider elevation and climate variables so site differences in soil and species competition need to be assessed using tools like local planting guilds and the Silvics of North America guild (Burns, 1990) before introducing any new species. This additional assessment is particularly important for low abundance species that may be niche specialists (e.g. riparian, specific soils, etc.) and alpine regions with more extreme climates. All these complicated factors and their interactions are why assisted migration field experiments like the ones planned by the DIVERSE project are best practice before operationally changing management practices especially when introducing new species.

Algonquin also has species that decrease in frequency over time (e.g. paper birch and balsam fir). When it comes to seed sourcing it's a great risk avoidance strategy to not push the fundamental niche limits, but rather plant within the realized niche (climates where species would naturally occur to reduce the risk of pests and diseases that also like the warmer climates. So, from a management perspective, when replanting it's best to shift to other species over time and if the site is used for timber, favor the harvest of the maladapted species to reduce risk.

Now looking at the Blue Ridge Lower foothills 1.3 ecosystem climate matches species frequencies, the 2020s and 2050s show promising species for population assisted migration (quaking aspen, black spruce, white spruce, lodgepole pine, balsam poplar, tamarack) (Table 3). However, in the 2080s climate matches, there are a lot of species that appear suddenly and sometimes at high frequencies (red maple and sugar maple). When new species appear suddenly and don't increase in frequency slowly over time it can indicate the species frequency is not the result of range expansion, but a lack of analog climate matches close enough for population and range expansion assisted migrations. The lack of analog climate matches can be verified in the next step.

Table 3. The downloadable species selection table provided by the tool for the lower foothills 1.3 ecosystem in the Blue Ridge forest management area. The values are the average of the 5 closest climate matches for each time period and all the values are in % area of the ecosystem.

Non-forested area is rescaled to remove human disturbance. The species' prevalences are scaled by non-forested area

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Expected Non-Forested	35.99	38.88	32.98	32.98	34.26
	Agriculture	13.74	4.51	29.40	29.40	14.93
Populus tremuloides	quaking aspen	20.47	16.33	27.85	27.85	11.59
Picea mariana	black spruce	15.21	15.87	12.47	12.47	4.06
Picea glauca	white spruce	10.43	10.30	10.64	10.64	2.96
Pinus contorta	lodgepole pine	8.91	11.80	6.23	6.23	0.65
Populus balsamifera	balsam poplar	4.26	2.48	5.47	5.47	2.29
Larix laricina	tamarack	2.41	2.29	2.07	2.07	1.37
Acer saccharum	sugar maple	0.00	0.00	0.00	0.00	9.45
Betula papyrifera	paper birch	1.60	1.31	1.62	1.62	1.56
Acer rubrum	red maple	0.00	0.00	0.00	0.00	6.18
Abies balsamea	balsam fir	0.54	0.55	0.46	0.46	3.37
Thuja occidentalis	northern white cedar	0.00	0.00	0.00	0.00	2.85
Pinus resinosa	red pine	0.00	0.00	0.00	0.00	2.47
Tsuga canadensis	eastern hemlock	0.00	0.00	0.00	0.00	2.16
Pinus strobus	eastern white pine	0.00	0.00	0.00	0.00	1.97
Tilia americana	American basswood	0.00	0.00	0.00	0.00	1.67
Fraxinus americana	white ash	0.00	0.00	0.00	0.00	1.66
Quercus rubra	northern red oak	0.00	0.00	0.00	0.00	1.49
Prunus serotina	black cherry	0.00	0.00	0.00	0.00	1.36
Betula alleghaniensis	yellow birch	0.00	0.00	0.00	0.00	1.32

4.3.3 Selecting appropriate seed sources

Once species for assisted migration are selected, the last step is the selection of seed sources. The tool displays the climate matched seed sources on a map (Figure 9) and provides a table of the seed source ecosystem names, jurisdiction, top ten most prevalent tree species and frequencies, forest cover, and the climate Euclidean distance of the seed source to the ecosystem's historic climate for all the time periods. The information in the table can then be used to obtain seedlings or seeds from the climate matched ecosystems. The bars to the right of the map (Figure 9) indicated the maximum Euclidean climate distances to use for the climate matched seed sources. For example, to get seed sources that are climatically close to the selected ecosystem's projected climate in the 2020s you would reduce the largest allowed Euclidean climatic distance on the 2020s slider (Figure 9).

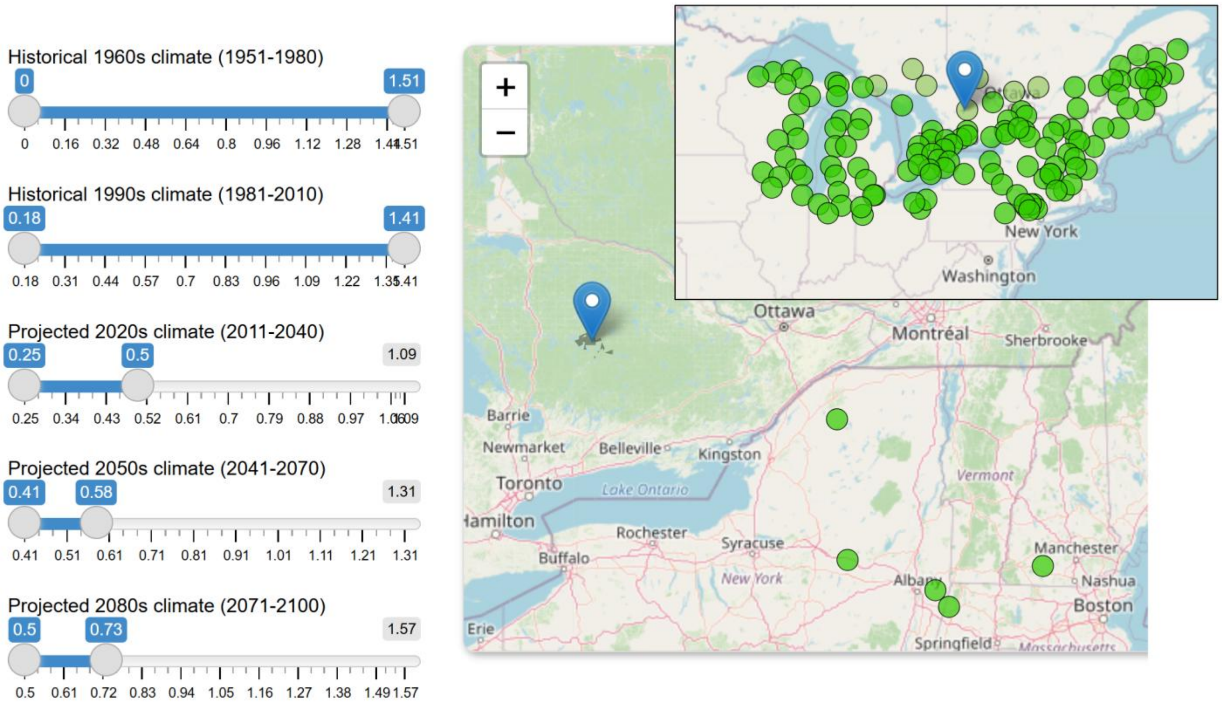


Figure 9. Climatic matches between a target ecosystem Algonquin (blue marker) and potential seed sources (circle markers) colored by biome. The sliders to the left indicate the user-set climate matching criteria in units of a scaled multivariate Euclidean distance. The upper right map shows the climate matches for all time periods

Currently, the average climate range of operational seed zones corresponds approximately to a scaled Euclidean distance of 0.5 from it's center, so if a slider is set to 0.5, this gives a range of ecosystem climates that are not unlike the typical climatic variance within most operational seed zones. Thus, 0.5 could be considered a good climate match in the absence of further analysis. While there are no fixed thresholds for no analogues, values above 1unit of the scaled climate distance approach no-analogue climate conditions.

When selecting seed sources with the tool it is important to keep in mind the lifespan of the species you are planting. If the species only has a 50 to 100 year life span like aspen, a good climate match for only one climate normal period is needed (Burns, 1990). For longer lived species like the ones selected for assisted population migration in Algonquin (sugar maple, norther red oak, red maple, and eastern white pine) (Burns, 1990) a favorable climate for longer is desired however if that is not possible a favorable climate during establishment and peak growth stages should be prioritized to increase seedling survival and later tree growth. That is why when narrowing down the climate matches for Algonquin the user can prioritize the 2020s (e.g. requiring Euclidean distance of 0.5 or less) so the climate is favorable when the trees are seedlings. However, favoring the 2020s climate means 2080s maximum Euclidean climate distance needs to be less strict for this site (0.75 or less). This is often the case due to the rapid projected rate of climate change. However, all five of the climate matches displayed in Figure 9 are still good candidates for assisted migration experiments and have the species selected above for Algonquin.

Looking at the lower foothills 1.3 ecosystem, the closest climate Euclidean distance is farther for all three climate projections than Algonquin (Figure 10). In the 2020s the closest climate match is good (Euclidean distance of 0.49) but in the 2080s the best climate match has a Euclidean distance of 0.9 approaching no analog climate confirming what the species tables (Table 3, and Figure 5) and biome shifts hinted at.

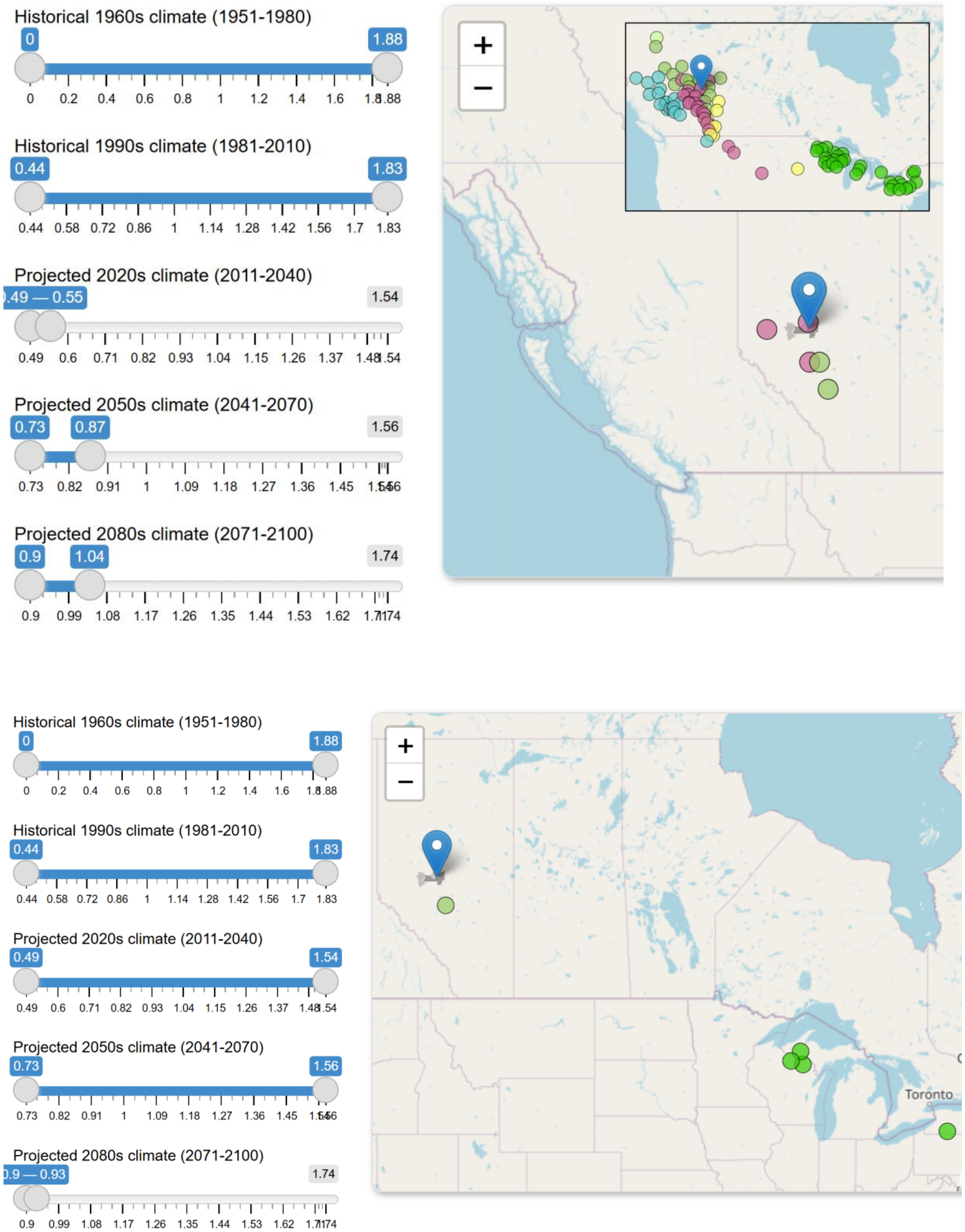


Figure 10. Climatic matches between a target ecosystem Lower Foothills 1.3. (blue marker) and potential seed sources (circle markers) colored by biome for two different user settings. The sliders to the left indicate the user-set climate matching criteria in units of a scaled multivariate Euclidean distance. The upper right map shows the climate matches for all time periods

Figure 10 illustrates that when there was no analog climate match for population or range expansion assisted migration the closest climate matches were transcontinental climate matches in the northeastern temperate forests. That is what led to the sudden appearance of sugar maple and red maple in the 2080s in the species frequency table (Table 3). However, even if the climate match was good (Euclidean distance of <=0.5) for the transcontinental seed sources there would still be no analog climate unless there was also a good climate match close enough to be used for population or range expansion assisted migration. That being said, of all the time periods no analog climate results are of least concern for the 2080s because it is not the current or near future planting conditions and it has the most uncertainty due to projecting the farthest into the future.

So, from a management perspective it is encouraging that there are still seed sources for population assisted migration in the 2020s and 2050s. Even though the climate matches in the 2050s are not ideal (Euclidean distances ranging from 0.73 to 0.83) the climate matches in Figure 10 are still the closest climate matches in North America for the 2020s and 20250s and the Lower foothills 1.3 ecosystem has already has observed climate change outside its historic envelope (Figure 8) in the 1990s so attempted assisted migration is still likely a better management strategy than inaction. That being said, there is elevated levels uncertainty for assisted migration experiments in this ecosystem due to the poor climate match in the 2050s and lack of analog in the 2080s. As climate chang realizes it will become clear if this site actually has no climate analog. If that does end up being the case the management implications of no climate analog are currently unclear.

4.4 General limitations and areas for future research

While it is known that the uncertainty of the climate projections increases as they project farther into the future, the uncertainty of the climate projections geographically across North America has not been quantified for this analysis. However, in most management scenarios this additional information would not impact decision making. For example, if the climate projection's uncertainty is high in an ecosystem the only course of action is to increase resilience through silvicultural practices and by following local planting guides to minimize risk. However, the DIVERSE team already plans to take these risk minimizing steps for all planting sites because ideally these risk reduction steps should be standard practice in all untested assisted migration plantations due to their experimental nature. The only case that the uncertainty of the climate projections could impact decision making is when selecting sites for assisted migration. For example, if the user is attempting to choose between different assisted migration sites due to limited resources. In this case the user could prioritize ecosystem with more confident future climate projections.

Another methodological limitation is that calculating the climate matches by using the Euclidean distance of the ecosystem's average climate assumes that the mean is a good representation of each ecosystem's climate. Even with the normalization of skewed variables this does not mathematically account for the range of the climate conditions experienced within the ecosystem. To minimize errors from this assumption I included every ecosystem in North America at a granular level and further divided them with elevation bands to reduce the climatic variation within them. However, dividing the ecosystems into elevation bands based on climate data alone, while time efficient, does not consider species distributions. This means the delineations do not necessarily delineate genetically or ecologically meaningful communities where I created the elevation contours. This aspect could be improved by future work to align elevation bands with changes in tree species community composition.

Future work could also incorporate species-specific seed zones or breeding regions that are in operational use in both Canada and the United States for major forestry species. Species-specific seed zones are often larger and climatically much wider than the level-4 ecosystem delineations (Campbell and Sugano, 1989). That is because the species have been proven not to be genetically differentiated at the finer scale. Nevertheless, climate matching can still be carried out for ecosystems to seed zones, from seed zones (seed orchards) to ecosystems, or from seed zones to seed zones, so future assisted migration tools could include these other types of geographic delineations that are in operational use. For example, a seed orchard manager may be interested in which ecosystems (outside their traditional breeding region) their improved planting stock may be used, or a forest company may want to see options including availability of improved planting stock from seed orchards for reforestation of a target site.

Another major limitation of this analysis is that it does not include any consideration of soil types. This means that the soil conditions at a target ecosystem are assumed to be comparable to those found at the recommended seed source locations, which may not always be true. Therefore, the users should consult available planting guidelines to determine what soil conditions and topographic positions species are typically planted in at the source ecosystems and apply the same guidelines to the target sites. Future research could incorporate soil types into seed source recommendations at the ecosystem level (through matching available soil variables, similar to an average ecosystem climate match) but matching species to exact local site conditions will remain a task that forest managers must determine for a specific planting site using knowledge of species' silvics and local site types.

5 Conclusions

Our approach of using ecosystem delineations as a proxy for climate conditions has some key practical advantages. Results of climate matches are easy to communicate in terms of where to source seeds to match target ecosystems within forest management areas for assisted migration (i.e. move from source ecosystem X to target ecosystem Y). However, no-analogue climates and potential mismatches of non-climatic site factors warrant testing the recommendations in trial plantations before using this or other assisted migration tools operationally. While this tool has limitations, I believe it is likely already preferable to status quo management, at least for 2020s recommendations to account for climate change that has already materialized. Test plantations that are established now (2020s) will require some time to yield results so the DIVERSE project is targeting the 2050s and 2080s climate conditions. Trial results will be available in 20-30 years as test plantations mature. If they are successful, this work will be an invaluable validation of assisted migration prescriptions that could provide confidence to recommend them at operational scales.

.

References

Abrams, M.D., Nowacki, G.J., 2008. Native Americans as active and passive promoters of mast and fruit trees in the eastern USA. The Holocene 18, 1123–1137.

Aitken, S.N., Bemmels, J.B., 2016. Time to get moving: assisted gene flow of forest trees. Evol. Appl. 9, 271–290.

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T., Curtis-McLane, S., 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol. Appl. 1, 95–111.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.T., others, 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manag. 259, 660–684.

Araújo, M.B., Peterson, A.T., 2012. Uses and misuses of bioclimatic envelope modeling. Ecology 93, 1527–1539.

Argüelles-Moyao, A., Garibay-Orijel, R., 2018. Ectomycorrhizal fungal communities in high mountain conifer forests in central Mexico and their potential use in the assisted migration of Abies religiosa. Mycorrhiza 28, 509–521.

Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., Rogelj, J., others, 2021. Climate Change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; technical summary.

Aubin, I., Garbe, C., Colombo, S., Drever, C., McKenney, D., Messier, C., Pedlar, J., Saner, M., Venier, L., Wellstead, A., others, 2011. Why we disagree about assisted migration: Ethical implications of a key debate regarding the future of Canada's forests. For. Chron. 87, 755–765.

Bates, C., 1930. The frost hardiness of geographic strains of Norway pine. J. For. 28, 327–333.

Beaudoin, A., Bernier, P., Villemaire, P., Guindon, L., Guo, X.J., 2018. Tracking forest attributes across Canada between 2001 and 2011 using ak nearest neighbors mapping approach applied to MODIS imagery. Can. J. For. Res. 48, 85–93.

Beaulieu, J., Rainville, A., 2005. Adaptation to climate change: genetic variation is both a short- and a long-term solution. For. Chron. 81, 704–709.

BEC Map, n.d.

Beery, S., Cole, E., Parker, J., Perona, P., Winner, K., 2021. Species distribution modeling for machine learning practitioners: A review, in: Proceedings of the 4th ACM SIGCAS Conference on Computing and Sustainable Societies. pp. 329–348.

Benito-Garzón, M., Fernández-Manjarrés, J.F., 2015. Testing scenarios for assisted migration of forest trees in Europe. New For. 46, 979–994.

Bennett, B.M., 2015. Plantations and protected areas: A global history of forest management. MIT Press.

Bentz, B.J., Régnière, J., Fettig, C.J., Hansen, E.M., Hayes, J.L., Hicke, J.A., Kelsey, R.G., Negrón, J.F., Seybold, S.J., 2010. Climate change and bark beetles of the western United States and Canada: direct and indirect effects. BioScience 60, 602–613.

Bonan, G.B., Sirois, L., 1992. Air temperature, tree growth, and the northern and southern range limits to Picea mariana. J. Veg. Sci. 3, 495–506.

Booth, T.H., 2018. Species distribution modelling tools and databases to assist managing forests under climate change. For. Ecol. Manag. 430, 196–203.

Bourdo Jr, E.A., 1955. A validation of methods used in analyzing original forest cover. University of Michigan.

Bower, A.D., Clair, J.B.S., Erickson, V., 2014. Generalized provisional seed zones for native plants. Ecol. Appl. 24, 913–919.

Brus, R., Pötzelsberger, E., Lapin, K., Brundu, G., Orazio, C., Straigyte, L., Hasenauer, H., 2019. Extent, distribution and origin of non-native forest tree species in Europe. Scand. J. For. Res. 34, 533–544.

Buri, A., Cianfrani, C., Pinto-Figueroa, E., Yashiro, E., Spangenberg, J.E., Adatte, T., Verrecchia, E., Guisan, A., Pradervand, J.-N., 2017. Soil factors improve predictions of plant species distribution in a mountain environment. Prog. Phys. Geogr. 41, 703–722.

Burns, R.M., 1990. Silvics of north America. US Department of Agriculture, Forest Service.

Campbell, R.K., Sugano, A.I., 1989. Seed zones and breeding zones for white pine in the Cascade Range of Washington and Oregon. US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Carbajal-Navarro, A., Navarro-Miranda, E., Blanco-García, A., Cruzado-Vargas, A.L., Gómez-Pineda, E., Zamora-Sánchez, C., Pineda-García, F., O'Neill, G., Gómez-Romero, M., Lindig-Cisneros, R., others, 2019. Ecological restoration of Abies religiosa forests using nurse plants and assisted migration in the Monarch Butterfly Biosphere Reserve, Mexico. Front. Ecol. Evol. 7, 421.

Cheng, J., Schloerke, B., Karambelkar, B., Xie, Y., 2025. leaflet: Create Interactive Web Maps with the JavaScript "Leaflet" Library.

Chludil, D., Čepl, J., Steffenrem, A., Stejskal, J., Sagariya, C., Pook, T., Schueler, S., Korecky̌, J., Almqvist, C., Chakraborty, D., others, 2025. A Pollen-Based Assisted Migration for Rapid Forest Adaptation. Glob. Change Biol. 31, e70014.

Chmura, D.J., Anderson, P.D., Howe, G.T., Harrington, C.A., Halofsky, J.E., Peterson, D.L., Shaw, D.C., Clair, J.B.S., 2011. Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. For. Ecol. Manag. 261, 1121–1142.

Coop, J.D., Parks, S.A., McClernan, S.R., Holsinger, L.M., 2016. Influences of prior wildfires on vegetation response to subsequent fire in a reburned Southwestern landscape. Ecol. Appl. 26, 346–354.

Davis, M.B., Shaw, R.G., 2001. Range shifts and adaptive responses to Quaternary climate change. Science 292, 673–679.

Delcourt, P.A., Delcourt, H.R., 1987. Long-term forest dynamics of the temperate zone. Springer.

DiMiceli, C., Townshend, J., Carroll, M., Sohlberg, R., 2021. Evolution of the representation of global vegetation by vegetation continuous fields. Remote Sens. Environ. 254, 112271.

Dumroese, R.K., Williams, M.I., Stanturf, J.A., Clair, J.B.S., 2015. Considerations for restoring temperate forests of tomorrow: forest restoration, assisted migration, and bioengineering. New For. 46, 947–964.

Etterson, J.R., Cornett, M.W., White, M.A., Kavajecz, L.C., 2020. Assisted migration across fixed seed zones detects adaptation lags in two major North American tree species. Ecol. Appl. 30, e02092.

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9, 1937–1958.

Feng, L., Sun, J., Shi, Y., Wang, G., Wang, T., 2020. Predicting suitable habitats of Camptotheca acuminata considering both climatic and soil variables. Forests 11, 891.

Fontaine, L.C., Larson, B.M., 2016. The right tree at the right place? Exploring urban foresters' perceptions of assisted migration. Urban For. Urban Green. 18, 221–227.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., Schepaschenko, D.G., 2015. Boreal forest health and global change. Science 349, 819–822.

Gillies, S., others, 2013. Rasterio: geospatial raster I/O for Python programmers.

Girardin, M.P., Isabel, N., Guo, X.J., Lamothe, M., Duchesne, I., Lenz, P., 2021. Annual aboveground carbon uptake enhancements from assisted gene flow in boreal black spruce forests are not long-lasting. Nat. Commun. 12, 1169.

Gobeyn, S., Mouton, A.M., Cord, A.F., Kaim, A., Volk, M., Goethals, P.L., 2019. Evolutionary algorithms for species distribution modelling: A review in the context of machine learning. Ecol. Model. 392, 179–195.

Gomez, C., Mangeas, M., Petit, M., Corbane, C., Hamon, P., Hamon, S., De Kochko, A., Le Pierres, D., Poncet, V., Despinoy, M., 2010. Use of high-resolution satellite imagery in an integrated model to predict the distribution of shade coffee tree hybrid zones. Remote Sens. Environ. 114, 2731–2744. https://doi.org/10.1016/j.rse.2010.06.007

Grady, K.C., Kolb, T.E., Ikeda, D.H., Whitham, T.G., 2015. A bridge too far: cold and pathogen constraints to assisted migration of riparian forests. Restor. Ecol. 23, 811–820.

Gray, A.N., Brandeis, T.J., Shaw, J.D., McWilliams, W.H., Miles, P., 2012. Forest inventory and analysis database of the United States of America (FIA). Dengler J Oldeland J Jansen F Chytry M Ewald J Finckh M Glockler F Lopez-Gonzalez G Peet RK Schaminee J HJ Eds Veg. Databases 21st Century Biodivers. Ecol. 4 225-231 225–231.

Gray, L.K., Hamann, A., 2013. Tracking suitable habitat for tree populations under climate change in western North America. Clim. Change 117, 289–303.

Griffith, B., Scott, J.M., Carpenter, J.W., Reed, C., 1989. Translocation as a species conservation tool: status and strategy. Science 245, 477–480.

Gustafson, E.J., Kern, C.C., Kabrick, J.M., 2023. Can assisted tree migration today sustain forest ecosystem goods and services for the future? For. Ecol. Manag. 529, 120723.

Hamann, A., Gylander, T., Chen, P., 2011. Developing seed zones and transfer guidelines with multivariate regression trees. Tree Genet. Genomes 7, 399–408.

Hamann, A., Wang, T., 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecology 87, 2773–2786.

Hampe, A., Petit, R.J., 2005. Conserving biodiversity under climate change: the rear edge matters. Ecol. Lett. 8, 461–467.

Hirsch, H., Allsopp, M.H., Canavan, S., Cheek, M., Geerts, S., Geldenhuys, C.J., Harding, G., Hurley, B.P., Jones, W., Keet, J.-H., others, 2020. Eucalyptus camaldulensis in South Africa–past, present, future. Trans. R. Soc. South Afr. 75, 1–22.

Hogg, E.H., 1994. Climate and the southern limit of the western Canadian boreal forest. Can. J. For. Res. 24, 1835–1845.

Iverson, L.R., Prasad, A.M., Peters, M.P., Matthews, S.N., 2019. Facilitating adaptive forest management under climate change: A spatially specific synthesis of 125 species for habitat changes and assisted migration over the eastern United States. Forests 10, 989.

Johnson, G., Sorensen, F.C., St Clair, J.B., Cronn, R.C., 2004. Pacific Northwest forest tree seed zones: a template for native plants? Native Plants J. 5, 131–140.

Johnson, R., Boyce, S., Brandt, L., Erickson, V., Iverson, L., Kujawa, G., Tkacz, B., 2013. Policy and strategy considerations for assisted migration on USDA Forest Service lands, in: In: Browning, J.; Palacios, P., Comps. Proceedings of the 60th Annual Western International Forest Disease Work Conference; 2012 October 8-12; Tahoe City, CA.[Place of Publication Unknown]: Western International Forest Disease Work Conference: 35-41. pp. 35–41.

Jordahl, K., Bossche, J.V. den, Fleischmann, M., Wasserman, J., McBride, J., Gerard, J., Tratner, J., Perry, M., Badaracco, A.G., Farmer, C., Hjelle, G.A., Snow, A.D., Cochran, M., Gillies, S., Culbertson, L., Bartos, M., Eubank, N., maxalbert, Bilogur, A., Rey, S., Ren, C., Arribas-Bel, D., Wasser, L., Wolf, L.J., Journois, M., Wilson, J., Greenhall, A., Holdgraf, C., Filipe, Leblanc, F., 2020. geopandas/geopandas: v0.8.1. https://doi.org/10.5281/zenodo.3946761

Jump, A.S., Peñuelas, J., 2005. Running to stand still: adaptation and the response of plants to rapid climate change. Ecol. Lett. 8, 1010–1020.

Kellison, R., Lea, R., Marsh, P., 2013. Introduction of Eucalyptus spp. into the United States with special emphasis on the southern United States. Int. J. For. Res. 2013, 189393.

King, G.A., Herstrom, A.A., 1997. Holocene tree migration rates objectively determined from fossil pollen data, in: Past and Future Rapid Environmental Changes: The Spatial and Evolutionary Responses of Terrestrial Biota. Springer, pp. 91–101.

Klenk, N.L., 2015. The development of assisted migration policy in Canada: An analysis of the politics of composing future forests. Land Use Policy 44, 101–109.

Koralewski, T.E., Wang, H.-H., Grant, W.E., Byram, T.D., 2015. Plants on the move: assisted migration of forest trees in the face of climate change. For. Ecol. Manag. 344, 30–37.

Ledig, F.T., Rehfeldt, G.E., Jaquish, B., 2012. Projections of suitable habitat under climate change scenarios: Implications for trans-boundary assisted colonization. Am. J. Bot. 99, 1217–1230.

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., Ruane, A.C., 2024. Climate change 2023 synthesis report summary for policymakers. Clim. CHANGE 2023 Synth. Rep. Summ. Policymakers.

Leech, S.M., Almuedo, P.L., O'Neill, G., 2011. Assisted migration: adapting forest management to a changing climate. J. Ecosyst. Manag. 12.

Lemprière, T., Bernier, P., Carroll, A., Flannigan, M., Gilsenan, R., McKenney, D., Hogg, E., Pedlar, J., Blain, D., 2008. The importance of forest sector adaptation to climate change.

Lenormand, T., 2002. Gene flow and the limits to natural selection. Trends Ecol. Evol. 17, 183–189.

Level IV Ecoregions of the Conterminous United States, 2013.

Li, X., Wang, Y., 2013. Applying various algorithms for species distribution modelling. Integr. Zool. 8, 124–135.

Linyucheva, A., Kindlmann, P., 2021. A review of global land cover maps in terms of their potential use for habitat suitability modelling. Eur. J. Environ. Sci. 11, 46–61.

Liu, C., White, M., Newell, G., 2009. Measuring the accuracy of species distribution models: a review, in: Proceedings 18th World IMACs/MODSIM Congress. Cairns, Australia. p. 4247.

Liu, Q., Peng, C., Schneider, R., Cyr, D., McDowell, N.G., Kneeshaw, D., 2023. Drought-induced increase in tree mortality and corresponding decrease in the carbon sink capacity of Canada's boreal forests from 1970 to 2020. Glob. Change Biol. 29, 2274–2285.

Lo, Y.-H., Blanco, J.A., Kimmins, J., Seely, B., Welham, C., 2011. Linking climate change and forest ecophysiology to project future trends in tree growth: A review of forest models. Clim. Chang. Technol. Adapt. Mitig. Rij. InTech 63–86.

MacKinnon, A., Meidinger, D., Klinka, K., 1992. Use of the biogeoclimatic ecosystem classification system in British Columbia. For. Chron. 68, 100–120.

Mahony, C.R., Wang, T., Hamann, A., Cannon, A.J., 2022. A global climate model ensemble for downscaled monthly climate normals over North America. Int. J. Climatol. 42, 5871–5891.

Malcolm, J.R., Markham, A., Neilson, R.P., Garaci, M., 2002. Estimated migration rates under scenarios of global climate change. J. Biogeogr. 29, 835–849.

Marshall, I.B., Scott Smith, C., Selby, C.J., 1996. A national framework for monitoring and reporting on environmental sustainability in Canada. Environ. Monit. Assess. 39, 25–38.

Martínez-Minaya, J., Cameletti, M., Conesa, D., Pennino, M.G., 2018. Species distribution modeling: a statistical review with focus in spatio-temporal issues. Stoch. Environ. Res. Risk Assess. 32, 3227–3244.

McKenney, D., Joyce, D., Mackey, B., 1999. Seedwhere: a computer tool to support seed transfer and ecological restoration decisions.

McKenney, D., Pedlar, J., O'Neill, G., 2009. Climate change and forest seed zones: Past trends, future prospects and challenges to ponder. For. Chron. 85, 258–266.

Mueller, J.M., Hellmann, J.J., 2008. An assessment of invasion risk from assisted migration. Conserv. Biol. 22, 562–567.

Myking, T., Rusanen, M., Steffenrem, A., Kjær, E.D., Jansson, G., 2016. Historic transfer of forest reproductive material in the Nordic region: drivers, scale and implications. For. Int. J. For. Res. 89, 325–337.

National Forest Inventory, n.d.

Nieto-Lugilde, D., Maguire, K.C., Blois, J.L., Williams, J.W., Fitzpatrick, M.C., 2018. Multiresponse algorithms for community-level modelling: Review of theory, applications, and comparison to species distribution models. Methods Ecol. Evol. 9, 834–848.

Notivol, E., Santos-del-Blanco, L., Chambel, R., Climent, J., Alía, R., 2020. Seed sourcing strategies considering climate change forecasts: A practical test in scots pine. Forests 11, 1222.

NRC (2006) Natural regions and Subregions of Alberta, n.d.

Omernik, J.M., Griffith, G.E., 2014. Ecoregions of the conterminous United States: evolution of a hierarchical spatial framework. Environ. Manage. 54, 1249–1266.

O'Neill, G., Carlson, M., Berger, V., Ukrainetz, N., 2013. Assisted migration adaptation trial: workplan. BC Minist. For. Lands Nat. Resour. Oper.

O'Neill, G., Wang, T., Ukrainetz, N., Charleson, L., McAuley, L., Yanchuk, A., Zedel, S., 2017. A proposed climate-based seed transfer system for British Columbia. Prov. BC, Victoria. BC Tech. Rep. 099. www. for. gov. bc. ca/hfd/pubs/Docs/Tr/Tr099. htm.

O'Neill, G.A., Gómez-Pineda, E., 2021. Local was best: sourcing tree seed for future climates. Can. J. For. Res. 51, 1432–1439.

Otis Prud'homme, G., Lamhamedi, M.S., Benomar, L., Rainville, A., DeBlois, J., Bousquet, J., Beaulieu, J., 2018. Ecophysiology and growth of white spruce seedlings from various seed sources along a climatic gradient support the need for assisted migration. Front. Plant Sci. 8, 2214.

Palik, B.J., Clark, P.W., D'Amato, A.W., Swanston, C., Nagel, L., 2022. Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. Ecosphere 13, e4260.

Park, A., Rodgers, J.L., 2023. Provenance trials in the service of forestry assisted migration: A review of North American field trials and experiments. For. Ecol. Manag. 537, 120854.

Park, A., Talbot, C., 2018. Information underload: ecological complexity, incomplete knowledge, and data deficits create challenges for the assisted migration of forest trees. BioScience 68, 251–263.

Pecchi, M., Marchi, M., Burton, V., Giannetti, F., Moriondo, M., Bernetti, I., Bindi, M., Chirici, G., 2019. Species distribution modelling to support forest management. A literature review. Ecol. Model. 411, 108817.

Pelai, R., Hagerman, S.M., Kozak, R., 2021. Whose expertise counts? Assisted migration and the politics of knowledge in British Columbia's public forests. Land Use Policy 103, 105296.

Peters, R.L., Darling, J.D.S., 1985. The greenhouse effect and nature reserves. Bioscience 35, 707–717.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rathore, M.K., Sharma, L.K., 2023. Efficacy of species distribution models (SDMs) for ecological realms to ascertain biological conservation and practices. Biodivers. Conserv. 32, 3053–3087.

Rehfeldt, G.E., Crookston, N.L., Sáenz-Romero, C., Campbell, E.M., 2012. North American vegetation model for land-use planning in a changing climate: A solution to large classification problems. Ecol. Appl. 22, 119–141.

Rehfeldt, G.E., Crookston, N.L., Warwell, M.V., Evans, J.S., 2006. Empirical analyses of plant-climate relationships for the western United States. Int. J. Plant Sci. 167, 1123–1150.

Ritchie, J.C., MacDonald, G.M., 1986. The patterns of post-glacial spread of white spruce. J. Biogeogr. 527–540.

Rossetto, M., Ens, E.J., Honings, T., Wilson, P.D., Yap, J.-Y.S., Costello, O., Round, E.R., Bowern, C., 2017. From songlines to genomes: prehistoric assisted migration of a rain forest tree by Australian Aboriginal people. PLoS One 12, e0186663.

Royo, A.A., Raymond, P., Kern, C.C., Adams, B.T., Bronson, D., Champagne, E., Dumais, D., Gustafson, E., Marquardt, P.E., McGraw, A.M., others, 2023. Desired REgeneration through Assisted Migration (DREAM): Implementing a research framework for climate-adaptive silviculture. For. Ecol. Manag. 546, 121298.

Sáenz-Romero, C., Mendoza-Maya, E., Gómez-Pineda, E., Blanco-García, A., Endara-Agramont, A.R., Lindig-Cisneros, R., López-Upton, J., Trejo-Ramírez, O., Wehenkel, C., Cibrián-Tovar, D., others, 2020. Recent evidence of Mexican temperate forest decline and the need for ex situ conservation, assisted migration, and translocation of species ensembles as adaptive management to face projected climatic change impacts in a megadiverse country. Can. J. For. Res. 50, 843–854.

Santini, L., Benítez-López, A., Maiorano, L., Čengić, M., Huijbregts, M.A., 2021. Assessing the reliability of species distribution projections in climate change research. Divers. Distrib. 27, 1035–1050.

Schaller, N., Mahlstein, I., Cermak, J., Knutti, R., 2011. Analyzing precipitation projections: A comparison of different approaches to climate model evaluation. J. Geophys. Res. Atmospheres 116.

Schimper, A.F.W., 1902. Plant-geography upon a physiological basis. Clarendon Press.

Schneider, R.R., Hamann, A., Farr, D., Wang, X., Boutin, S., 2009. Potential effects of climate change on ecosystem distribution in Alberta. Can. J. For. Res. 39, 1001–1010.

Schneider, S.H., 2004. Abrupt non-linear climate change, irreversibility and surprise. Glob. Environ. Change 14, 245–258.

Sittaro, F., Paquette, A., Messier, C., Nock, C.A., 2017. Tree range expansion in eastern North America fails to keep pace with climate warming at northern range limits. Glob. Change Biol. 23, 3292–3301.

St. Clair, J.B., Richardson, B.A., Stevenson-Molnar, N., Howe, G.T., Bower, A.D., Erickson, V.J., Ward, B., Bachelet, D., Kilkenny, F.F., Wang, T., 2022. Seedlot Selection Tool and Climate-Smart Restoration Tool: Web-based tools for sourcing seed adapted to future climates. Ecosphere 13, e4089.

Stanturf, J.A., Ivetić, V., Dumroese, R.K., 2024. Framing recent advances in assisted migration of trees: a special issue. For. Ecol. Manag.

Stuber, R.J., 1982. Habitat suitability index models: black bullhead. Western Energy and Land Use Team, Office of Biological Services, Fish and ….

Taïbi, K., Del Campo, A., Aguado, A., Mulet, J., 2016. Early establishment response of different Pinus nigra ssp. salzmanii seed sources on contrasting environments: Implications for future reforestation programs and assisted population migration. J. Environ. Manage. 171, 184–194.

team, T. pandas development, 2020. pandas-dev/pandas: Pandas. https://doi.org/10.5281/zenodo.3509134

Terrestrial Ecodistricts of Canada, 2013.

Ukrainetz, N.K., O'Neill, G.A., Jaquish, B., 2011. Comparison of fixed and focal point seed transfer systems for reforestation and assisted migration: a case study for interior spruce in British Columbia. Can. J. For. Res. 41, 1452–1464.

Van Daele, F., Honnay, O., De Kort, H., 2022. Genomic analyses point to a low evolutionary potential of prospective source populations for assisted migration in a forest herb. Evol. Appl. 15, 1859–1874.

Van Rossum, G., Drake Jr, F.L., 1995. Python reference manual. Centrum voor Wiskunde en Informatica Amsterdam.

Vitt, P., Havens, K., Kramer, A.T., Sollenberger, D., Yates, E., 2010. Assisted migration of plants: changes in latitudes, changes in attitudes. Biol. Conserv. 143, 18–27.

Waldock, C., Stuart-Smith, R.D., Albouy, C., Cheung, W.W., Edgar, G.J., Mouillot, D., Tjiputra, J., Pellissier, L., 2022. A quantitative review of abundance-based species distribution models. Ecography 2022.

Wang, L., Diao, C., Lu, Y., 2025. The role of remote sensing in species distribution models: a review. Int. J. Remote Sens. 46, 661–685.

Wang, T., Hamann, A., Spittlehouse, D., Carroll, C., 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PloS One 11, e0156720.

Whitman, E., Parisien, M.-A., Thompson, D.K., Flannigan, M.D., 2019. Short-interval wildfire and drought overwhelm boreal forest resilience. Sci. Rep. 9, 18796.

Williams, J.W., Jackson, S.T., 2007. Novel climates, no-analog communities, and ecological surprises. Front. Ecol. Environ. 5, 475–482.

Williams, M.I., Dumroese, R.K., 2014. Planning the future's forests with assisted migration, in: In: Sample, V. Alaric; Bixler, R. Patrick, Eds. Forest Conservation and Management in the Anthropocene: Conference Proceedings. Proceedings. RMRS-P-71. Fort Collins, CO: US Department of Agriculture, Forest Service. Rocky Mountain Research Station. p. 133-144. pp. 133–144.

Williams, M.I., Dumroese, R.K., 2013. Growing assisted migration: Synthesis of a climate change adaptation strategy. Haase DL Pinto JR Wilkinson KM Tech. Coord. Natl. Proc. For. Conserv. Nurs. Assoc.-2012 Proc. RMRS-P-69 Fort Collins CO US Dep. Agric. For. Serv. Rocky Mt. Res. Stn. P 90-96 69, 90–96.

Wilson, B.T., Lister, A.J., Riemann, R.I., 2012. A nearest-neighbor imputation approach to mapping tree species over large areas using forest inventory plots and moderate resolution raster data. For. Ecol. Manag. 271, 182–198.

Winder, R., Nelson, E., Beardmore, T., 2011. Ecological implications for assisted migration in Canadian forests. For. Chron. 87, 731–744.

Xu, W., Prescott, C.E., 2024. Can assisted migration mitigate climate-change impacts on forests? For. Ecol. Manag. 556, 121738.

Young, D.J., Blush, T.D., Landram, M., Wright, J.W., Latimer, A.M., Safford, H.D., 2020. Assisted gene flow in the context of large-scale forest management in California, USA. Ecosphere 11, e03001.

Zhu, K., Woodall, C.W., Clark, J.S., 2012. Failure to migrate: lack of tree range expansion in response to climate change. Glob. Change Biol. 18, 1042–1052.

Zimmerman, Z., Boyce, N., Hamann, A., 2025. A deep learning approach to species distribution modeling for North American tree species., in: Proceedings of Forest Genetics 2025: Presented at the the 38th annual Southern Forest Tree Improvement Committee, and Western, and Northern Forest Genetics Association Joint Conference, Hamilton, J.A. and Gottlieb, R. (Eds.)Hamilton, J.A. and Gottlieb, R. (Eds.), State College, PA, pp. 78–79.

Appendix

Table A1. Atikamekw territory: Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	34.48	30.21	32.04	31.41	28.79
	Agriculture	0.05	1.94	4.22	10.78	9.87
Picea mariana	black spruce	18.60	9.92	3.82	0.51	0.31
Betula papyrifera	paper birch	13.73	11.26	6.65	2.10	1.66
Pinus banksiana	jack pine	6.55	2.89	0.88	0.19	0.16
Abies balsamea	balsam fir	6.42	9.26	11.90	5.69	4.43
Populus tremuloides	quaking aspen	6.13	5.62	4.19	2.05	1.69
Betula alleghaniensis	yellow birch	3.57	6.62	6.57	4.68	4.52
Picea glauca	white spruce	3.00	3.45	2.82	0.74	0.43
Acer saccharum	sugar maple	1.75	6.89	9.24	9.41	9.68
Acer rubrum	red maple	1.43	4.11	6.34	11.84	12.71
Thuja occidentalis	northern white cedar	1.25	2.79	4.38	1.89	1.25
Pinus strobus	eastern white pine	0.59	0.87	0.84	4.51	5.79
Larix laricina	tamarack	0.42	0.45	0.44	0.31	0.29
Picea rubens	red spruce	0.39	1.41	3.57	3.14	2.90
Populus grandidentata	bigtooth aspen	0.22	0.70	0.72	0.86	0.80
Picea abies	Norway spruce	0.21	0.15	0.08	0.32	0.42
Fagus grandifolia	American beech	0.14	0.94	1.56	4.01	4.66
Populus balsamifera	balsam poplar	0.12	0.16	0.24	0.13	0.10
Tsuga canadensis	eastern hemlock	0.08	0.58	1.15	5.49	6.83
Fraxinus nigra	black ash	0.06	0.17	0.24	0.22	0.20
Pinus resinosa	red pine	0.06	0.12	0.15	0.52	0.59
Tilia americana	American basswood	0.03	0.21	0.29	0.39	0.46
Quercus rubra	northern red oak	0.02	0.12	0.15	1.68	2.31
Fraxinus americana	white ash	0.01	0.08	0.21	2.27	2.52
Prunus serotina	black cherry	0.01	0.04	0.09	2.30	2.82
Acer saccharinum	silver maple	0.00	0.06	0.09	0.06	0.05
Fraxinus pennsylvanica	green ash	0.00	0.01	0.03	0.08	0.07
Ulmus americana	American elm	0.00	0.00	0.02	0.22	0.24
Carya cordiformis	bitternut hickory	0.00	0.00	0.00	0.09	0.11
Quercus alba	white oak	0.00	0.00	0.00	0.09	0.11
Quercus velutina	black oak	0.00	0.00	0.01	0.05	0.05

Table 2A. Babine Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	39.72	37.58	38.22	37.93	41.72
	Agriculture	0.23	0.24	0.72	1.61	2.00
Pinus contorta	lodgepole pine	24.77	22.55	15.26	11.80	7.65
Abies lasiocarpa	subalpine fir	6.79	6.15	4.78	3.95	2.36
Picea glauca	white spruce	5.35	4.27	3.70	2.43	0.47
Populus tremuloides	quaking aspen	4.61	4.38	6.41	4.83	2.54
Pseudotsuga menziesii	Douglas fir	2.10	6.97	12.05	14.84	16.81
Picea engelmannii	Engelmann spruce	0.56	1.33	1.70	2.31	2.72
Picea mariana	black spruce	0.54	0.39	0.36	0.17	0.05
Betula papyrifera	paper birch	0.53	0.83	1.88	1.58	1.17
Tsuga mertensiana	mountain hemlock	0.50	0.46	0.32	0.22	0.35
Tsuga heterophylla	western hemlock	0.50	0.99	1.26	1.84	2.60
Populus balsamifera	balsam poplar	0.44	0.43	0.74	0.62	0.39
Thuja plicata	western redcedar	0.18	1.02	1.81	3.41	5.11
Abies amabilis	Pacific silver fir	0.12	0.38	0.35	0.42	0.49
Pinus albicaulis	whitebark pine	0.06	0.14	0.08	0.15	0.16
Chamaecyparis nootkatensis	Alaska cedar	0.05	0.06	0.05	0.07	0.08
Populus trichocarpa	black cottonwood	0.03	0.01	0.01	0.05	0.18
Larix occidentalis	western larch	0.01	0.05	0.67	1.95	3.50
Pinus monticola	western white pine	0.01	0.05	0.11	0.35	0.56
Abies balsamea	balsam fir	0.01	0.02	0.03	0.03	0.03
Pinus ponderosa	ponderosa pine	0.00	0.02	0.14	0.40	1.25
Picea sitchensis	Sitka spruce	0.00	0.02	0.02	0.03	0.05
Alnus rubra	red alder	0.00	0.03	0.03	0.06	0.09
Abies grandis	grand fir	0.00	0.01	0.01	0.26	2.30
Acer saccharum	sugar maple	0.00	0.00	0.02	0.07	0.15
Thuja occidentalis	northern white cedar	0.00	0.00	0.02	0.03	0.05
Pinus strobus	eastern white pine	0.00	0.00	0.01	0.03	0.06
Acer rubrum	red maple	0.00	0.00	0.01	0.03	0.12
Fraxinus americana	white ash	0.00	0.00	0.01	0.03	0.07
Quercus rubra	northern red oak	0.00	0.00	0.01	0.02	0.06
Tsuga canadensis	eastern hemlock	0.00	0.00	0.00	0.02	0.05
Fagus grandifolia	American beech	0.00	0.00	0.00	0.01	0.05

Table 3A. Blue Ridge Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	32.35	32.73	36.23	39.03	37.38
	Agriculture	15.35	10.76	24.33	29.20	15.18
Populus tremuloides	quaking aspen	21.34	17.66	20.99	21.93	10.45
Picea mariana	black spruce	14.47	15.83	13.33	11.62	4.59
Pinus contorta	lodgepole pine	11.32	13.79	9.08	7.23	1.87
Picea glauca	white spruce	10.00	10.58	9.58	8.73	3.04
Populus balsamifera	balsam poplar	4.25	2.94	4.13	4.37	1.79
Larix laricina	tamarack	2.04	2.03	1.99	1.84	1.23
Betula papyrifera	paper birch	1.29	1.29	1.38	1.38	1.35
Abies balsamea	balsam fir	0.66	0.87	0.64	0.61	2.95
Pinus banksiana	jack pine	0.23	0.14	0.16	0.18	0.53
Picea engelmannii	Engelmann spruce	0.11	0.13	0.06	0.03	0.04
Abies lasiocarpa	subalpine fir	0.05	0.10	0.03	0.02	0.01
Pseudotsuga menziesii	Douglas fir	0.01	0.04	0.01	0.09	0.40
Pinus strobus	eastern white pine	0.00	0.00	0.00	0.02	1.54
Thuja occidentalis	northern white cedar	0.00	0.00	0.00	0.06	2.38
Fraxinus nigra	black ash	0.00	0.00	0.00	0.05	0.87
Fraxinus pennsylvanica	green ash	0.00	0.00	0.00	0.05	0.13
Pinus resinosa	red pine	0.00	0.00	0.00	0.05	1.96
Acer rubrum	red maple	0.00	0.00	0.00	0.04	5.20
Acer saccharum	sugar maple	0.00	0.00	0.00	0.03	8.23
Tilia americana	American basswood	0.00	0.00	0.00	0.02	1.61
Quercus rubra	northern red oak	0.00	0.00	0.00	0.01	1.24
Populus grandidentata	bigtooth aspen	0.00	0.00	0.00	0.01	0.80
Betula alleghaniensis	yellow birch	0.00	0.00	0.00	0.00	1.15
Ulmus americana	American elm	0.00	0.00	0.00	0.00	0.23
Pinus ponderosa	ponderosa pine	0.00	0.00	0.00	0.00	0.34
Tsuga canadensis	eastern hemlock	0.00	0.00	0.00	0.00	1.77
Prunus serotina	black cherry	0.00	0.00	0.00	0.00	1.10
Acer saccharinum	silver maple	0.00	0.00	0.00	0.00	0.02
Fraxinus americana	white ash	0.00	0.00	0.00	0.00	1.35
Fagus grandifolia	American beech	0.00	0.00	0.00	0.00	0.80
Picea abies	Norway spruce	0.00	0.00	0.00	0.00	0.28
Pinus sylvestris	Scots pine	0.00	0.00	0.00	0.00	0.18
Quercus alba	white oak	0.00	0.00	0.00	0.00	0.15
Carya cordiformis	bitternut hickory	0.00	0.00	0.00	0.00	0.11
Quercus prinus	chestnut oak	0.00	0.00	0.00	0.00	0.10

Table 4A. Bois Francs Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	33.67	33.20	49.42	46.98	28.11
	Agriculture	22.74	13.88	23.58	24.79	30.12
Abies balsamea	balsam fir	11.63	11.32	1.78	0.58	0.13
Acer rubrum	red maple	7.92	8.62	8.53	9.99	12.92
Thuja occidentalis	northern white cedar	5.95	6.54	1.53	0.59	0.05
Acer saccharum	sugar maple	5.78	4.78	6.22	3.49	3.84
Betula papyrifera	paper birch	4.53	3.68	1.06	0.54	0.45
Populus tremuloides	quaking aspen	4.51	3.55	1.66	0.79	0.66
Picea rubens	red spruce	4.29	4.59	1.09	0.56	0.17
Betula alleghaniensis	yellow birch	3.88	3.58	2.16	1.27	0.85
Picea mariana	black spruce	2.70	1.97	0.14	0.02	0.01
Tsuga canadensis	eastern hemlock	2.28	3.91	4.26	4.70	5.46
Picea glauca	white spruce	2.18	1.62	0.33	0.06	0.04
Fagus grandifolia	American beech	1.64	1.89	2.38	1.76	1.59
Pinus strobus	eastern white pine	1.46	3.06	4.12	7.89	8.17
Larix laricina	tamarack	0.82	0.68	0.25	0.13	0.16
Populus grandidentata	bigtooth aspen	0.67	0.78	0.87	0.49	0.61
Fraxinus americana	white ash	0.65	0.91	2.55	2.06	3.16
Pinus banksiana	jack pine	0.49	0.41	0.08	0.03	0.02
Fraxinus nigra	black ash	0.35	0.42	0.49	0.23	0.06
Populus balsamifera	balsam poplar	0.32	0.18	0.09	0.03	0.00
Quercus rubra	northern red oak	0.26	0.42	1.50	3.93	6.49
Pinus resinosa	red pine	0.25	0.38	0.51	0.35	0.35
Tilia americana	American basswood	0.16	0.18	0.78	0.52	0.51
Prunus serotina	black cherry	0.12	0.22	1.66	1.82	2.47
Acer saccharinum	silver maple	0.09	0.09	0.26	0.31	0.35
Ulmus americana	American elm	0.08	0.11	0.70	0.67	0.76
Picea abies	Norway spruce	0.07	0.07	0.34	0.19	0.23
Fraxinus pennsylvanica	green ash	0.05	0.06	0.24	0.24	0.29
Quercus velutina	black oak	0.03	0.02	0.07	1.49	2.36
Quercus alba	white oak	0.02	0.02	0.18	1.40	3.75
Carya cordiformis	bitternut hickory	0.01	0.01	0.23	0.22	0.31
Juniperus virginiana	eastern redcedar	0.00	0.00	0.06	0.25	0.44
Pinus sylvestris	Scots pine	0.00	0.01	0.22	0.17	0.13
Carya ovata	shagbark hickory	0.00	0.00	0.08	0.36	0.70

Table 5A. Chilliwack Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	53.53	45.73	43.89	42.43	36.40
	Agriculture	1.44	1.52	2.40	5.29	3.37
Pseudotsuga menziesii	Douglas fir	10.95	14.25	16.67	18.89	22.99
Tsuga heterophylla	western hemlock	8.10	10.57	8.55	8.07	9.87
Abies amabilis	Pacific silver fir	3.88	5.59	3.90	4.34	4.70
Thuja plicata	western redcedar	3.52	4.22	4.90	4.29	4.65
Tsuga mertensiana	mountain hemlock	3.11	2.49	2.19	2.01	1.90
Alnus rubra	red alder	1.79	2.20	1.95	2.22	2.44
Abies lasiocarpa	subalpine fir	1.50	1.57	1.76	1.48	1.33
Chamaecyparis nootkatensis	Alaska cedar	1.44	1.52	1.18	1.04	0.98
Pinus contorta	lodgepole pine	0.85	0.71	1.35	1.24	0.89
Acer macrophyllum	bigleaf maple	0.53	0.55	0.73	0.87	0.96
Picea sitchensis	Sitka spruce	0.53	0.66	0.39	0.32	0.36
Picea engelmannii	Engelmann spruce	0.24	0.32	0.79	0.58	0.58
Abies procera	noble fir	0.23	0.36	0.29	0.29	0.45
Populus trichocarpa	black cottonwood	0.22	0.17	0.22	0.25	0.26
Abies grandis	grand fir	0.17	0.15	2.58	1.93	2.06
Picea glauca	white spruce	0.16	0.05	0.04	0.02	0.00
Populus balsamifera	balsam poplar	0.15	0.13	0.08	0.16	0.02
Pinus albicaulis	whitebark pine	0.15	0.15	0.10	0.09	0.08
Abies balsamea	balsam fir	0.15	0.08	0.07	0.01	0.00
Picea mariana	black spruce	0.14	0.08	0.07	0.01	0.00
Betula papyrifera	paper birch	0.12	0.11	0.12	0.13	0.06
Populus tremuloides	quaking aspen	0.11	0.11	0.09	0.11	0.03
Pinus ponderosa	ponderosa pine	0.08	0.06	0.32	0.26	0.27
Acer rubrum	red maple	0.08	0.14	0.14	0.01	0.15
Pinus monticola	western white pine	0.07	0.05	0.20	0.19	0.19
Larix occidentalis	western larch	0.05	0.06	0.70	0.51	0.49
Abies concolor	white fir	0.04	0.04	0.06	0.08	0.12
Picea rubens	red spruce	0.03	0.18	0.18	0.01	0.00
Acer saccharum	sugar maple	0.03	0.02	0.02	0.00	0.07
Pinus lambertiana	sugar pine	0.00	0.01	0.03	0.09	0.12
Quercus rubra	northern red oak	0.00	0.01	0.01	0.00	0.13
Pinus strobus	eastern white pine	0.00	0.06	0.06	0.00	0.04
Sequoia sempervirens	redwood	0.00	0.00	0.00	0.08	0.08

Table 6A. Grand Prairie Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	34.22	36.55	38.46	47.87	54.14
	Agriculture	11.88	13.64	18.42	28.85	25.06
Populus tremuloides	quaking aspen	18.98	16.23	18.83	17.44	9.62
Pinus contorta	lodgepole pine	15.19	15.35	11.63	7.86	2.35
Picea mariana	black spruce	11.34	11.67	10.92	8.62	2.66
Picea glauca	white spruce	9.25	9.33	8.62	6.67	2.74
Populus balsamifera	balsam poplar	3.44	2.94	3.64	3.33	1.63
Picea engelmannii	Engelmann spruce	1.56	1.49	0.89	0.67	0.59
Larix laricina	tamarack	1.33	1.19	1.43	1.25	0.71
Betula papyrifera	paper birch	0.84	0.84	0.98	0.89	1.06
Abies lasiocarpa	subalpine fir	0.80	0.89	0.67	0.43	0.48
Abies balsamea	balsam fir	0.72	0.94	0.72	0.48	1.15
Pinus banksiana	jack pine	0.23	0.11	0.11	0.10	0.19
Pseudotsuga menziesii	Douglas fir	0.18	0.18	0.46	1.23	2.46
Pinus albicaulis	whitebark pine	0.03	0.03	0.06	0.08	0.06
Larix occidentalis	western larch	0.03	0.03	0.09	0.15	0.28
Thuja plicata	western redcedar	0.01	0.01	0.02	0.01	0.32
Tsuga heterophylla	western hemlock	0.01	0.01	0.01	0.01	0.06
Populus trichocarpa	black cottonwood	0.01	0.01	0.01	0.01	0.02
Pinus strobus	eastern white pine	0.00	0.00	0.00	0.00	0.57
Pinus ponderosa	ponderosa pine	0.00	0.00	0.00	0.48	3.72
Abies grandis	grand fir	0.00	0.00	0.00	0.00	0.42
Thuja occidentalis	northern white cedar	0.00	0.00	0.00	0.00	1.02
Acer saccharum	sugar maple	0.00	0.00	0.00	0.00	3.72
Acer rubrum	red maple	0.00	0.00	0.00	0.00	2.16
Tsuga canadensis	eastern hemlock	0.00	0.00	0.00	0.00	0.74
Tilia americana	American basswood	0.00	0.00	0.00	0.00	0.73
Pinus resinosa	red pine	0.00	0.00	0.00	0.00	0.68
Fraxinus americana	white ash	0.00	0.00	0.00	0.00	0.56
Betula alleghaniensis	yellow birch	0.00	0.00	0.00	0.00	0.52
Quercus rubra	northern red oak	0.00	0.00	0.00	0.00	0.46
Prunus serotina	black cherry	0.00	0.00	0.00	0.00	0.45
Fraxinus nigra	black ash	0.00	0.00	0.00	0.00	0.36
Fagus grandifolia	American beech	0.00	0.00	0.00	0.00	0.32
Populus grandidentata	bigtooth aspen	0.00	0.00	0.00	0.00	0.31
Fraxinus pennsylvanica	green ash	0.00	0.00	0.00	0.00	0.14

Table 7A. Haliburton Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	**Common name**	**1960s**	**1990s**	**2020s**	**2050s**	**2080s**
	Non-Forested	39.07	34.29	38.29	32.35	36.52
	Agriculture	4.69	4.61	20.82	36.55	76.30
Acer saccharum	sugar maple	10.75	7.72	6.76	6.38	3.09
Pinus strobus	eastern white pine	5.07	7.80	7.05	5.18	1.72
Betula papyrifera	paper birch	4.59	4.05	1.39	0.48	0.16
Acer rubrum	red maple	4.54	6.84	8.94	9.35	5.21
Abies balsamea	balsam fir	4.25	4.14	1.79	0.30	0.03
Betula alleghaniensis	yellow birch	3.40	3.04	1.75	0.96	0.23
Tsuga canadensis	eastern hemlock	3.18	6.03	6.57	4.23	0.59
Thuja occidentalis	northern white cedar	2.87	1.68	1.95	1.52	0.55
Quercus rubra	northern red oak	2.43	3.14	2.89	3.63	3.27
Populus tremuloides	quaking aspen	2.06	0.98	1.31	2.08	1.12
Picea glauca	white spruce	1.70	1.03	0.32	0.18	0.48
Picea mariana	black spruce	1.42	0.93	0.06	0.02	0.01
Fagus grandifolia	American beech	1.40	3.06	2.62	1.90	0.61
Populus grandidentata	bigtooth aspen	0.84	0.56	0.62	1.42	0.66
Tilia americana	American basswood	0.82	0.32	0.83	1.74	1.96
Pinus banksiana	jack pine	0.81	0.69	0.04	0.50	0.69
Pinus resinosa	red pine	0.76	0.70	0.67	2.52	1.30
Fraxinus americana	white ash	0.72	1.58	3.28	3.60	1.92
Picea rubens	red spruce	0.71	2.11	1.17	0.12	0.01
Fraxinus nigra	black ash	0.63	0.34	0.44	0.62	0.51
Acer saccharinum	silver maple	0.56	0.52	0.10	0.56	2.13
Larix laricina	tamarack	0.43	0.35	0.14	0.15	0.23
Prunus serotina	black cherry	0.43	1.02	2.21	3.13	4.43
Populus balsamifera	balsam poplar	0.11	0.06	0.06	0.05	0.01
Ulmus americana	American elm	0.11	0.15	0.70	1.38	2.73
Quercus alba	white oak	0.08	0.11	0.36	2.56	3.52
Fraxinus pennsylvanica	green ash	0.06	0.04	0.21	1.43	3.75
Picea abies	Norway spruce	0.03	0.21	0.57	0.58	0.18
Carya cordiformis	bitternut hickory	0.03	0.05	0.29	0.40	0.84
Pinus sylvestris	Scots pine	0.03	0.08	0.26	0.42	0.54
Juniperus virginiana	eastern redcedar	0.03	0.03	0.08	0.18	1.03
Quercus velutina	black oak	0.02	0.03	0.15	1.28	2.10
Populus deltoides	eastern cottonwood	0.01	0.01	0.04	0.31	2.34
Carya ovata	shagbark hickory	0.01	0.02	0.17	0.54	1.06

Table 8A. Kamloops Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	32.92	34.56	45.10	57.94	61.08
	Agriculture	0.06	0.04	0.24	2.21	1.99
Pinus contorta	lodgepole pine	30.78	24.46	16.30	6.24	4.50
Pseudotsuga menziesii	Douglas fir	8.62	10.47	14.02	13.16	12.86
Abies lasiocarpa	subalpine fir	4.82	5.45	3.76	2.72	2.12
Picea engelmannii	Engelmann spruce	3.98	5.01	3.86	2.91	2.37
Populus tremuloides	quaking aspen	2.74	2.39	1.65	0.90	0.16
Picea glauca	white spruce	2.54	1.60	0.56	0.12	0.00
Larix occidentalis	western larch	1.18	2.22	3.91	3.50	3.03
Thuja plicata	western redcedar	0.82	1.12	1.44	1.47	1.72
Betula papyrifera	paper birch	0.35	0.41	0.35	0.18	0.20
Picea mariana	black spruce	0.26	0.15	0.01	0.00	0.00
Tsuga heterophylla	western hemlock	0.24	0.34	0.46	0.44	0.38
Populus balsamifera	balsam poplar	0.16	0.17	0.14	0.05	0.00
Pinus albicaulis	whitebark pine	0.14	0.14	0.24	0.17	0.14
Pinus monticola	western white pine	0.09	0.13	0.19	0.16	0.14
Pinus ponderosa	ponderosa pine	0.08	0.13	1.53	3.95	4.93
Abies amabilis	Pacific silver fir	0.02	0.05	0.04	0.02	0.02
Tsuga mertensiana	mountain hemlock	0.00	0.02	0.16	0.51	0.55
Abies grandis	grand fir	0.00	0.05	1.07	3.91	4.90
Populus trichocarpa	black cottonwood	0.00	0.00	0.05	0.15	0.15
Abies concolor	white fir	0.00	0.00	0.03	0.19	0.34

Table 9A. Kenauk Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	29.21	29.32	31.83	24.12	24.03
	Agriculture	3.01	3.23	8.64	8.85	18.19
Abies balsamea	balsam fir	12.71	12.78	5.13	2.83	0.99
Acer saccharum	sugar maple	9.92	9.93	9.21	9.95	8.46
Betula papyrifera	paper birch	7.29	7.22	2.08	1.71	1.20
Betula alleghaniensis	yellow birch	6.77	6.75	4.13	4.37	2.82
Acer rubrum	red maple	5.93	6.01	11.01	13.50	13.57
Picea mariana	black spruce	4.79	4.77	0.33	0.05	0.01
Thuja occidentalis	northern white cedar	4.29	4.29	1.62	0.64	0.25
Populus tremuloides	quaking aspen	3.86	3.90	1.79	1.08	1.11
Picea rubens	red spruce	3.75	3.79	3.31	3.10	1.06
Picea glauca	white spruce	3.09	3.08	0.55	0.12	0.08
Fagus grandifolia	American beech	1.55	1.55	4.37	5.61	3.98
Pinus strobus	eastern white pine	0.83	0.75	5.71	7.49	8.96
Pinus banksiana	jack pine	0.80	0.78	0.17	0.01	0.01
Tsuga canadensis	eastern hemlock	0.70	0.71	6.54	8.78	8.73
Populus grandidentata	bigtooth aspen	0.66	0.65	0.95	0.83	0.74
Larix laricina	tamarack	0.45	0.45	0.26	0.21	0.15
Tilia americana	American basswood	0.23	0.23	0.40	0.45	0.60
Populus balsamifera	balsam poplar	0.21	0.21	0.12	0.03	0.02
Fraxinus nigra	black ash	0.20	0.20	0.24	0.16	0.12
Pinus resinosa	red pine	0.19	0.17	0.40	0.58	0.60
Fraxinus americana	white ash	0.17	0.17	2.26	3.08	3.89
Quercus rubra	northern red oak	0.15	0.13	2.03	3.32	6.38
Picea abies	Norway spruce	0.09	0.09	0.42	0.47	0.29
Acer saccharinum	silver maple	0.08	0.07	0.05	0.03	0.07
Prunus serotina	black cherry	0.06	0.06	1.82	3.04	3.26
Fraxinus pennsylvanica	green ash	0.01	0.01	0.06	0.07	0.15
Ulmus americana	American elm	0.01	0.01	0.23	0.29	0.39
Quercus alba	white oak	0.00	0.00	0.09	0.14	0.61
Carya cordiformis	bitternut hickory	0.00	0.00	0.07	0.14	0.25
Quercus velutina	black oak	0.00	0.00	0.04	0.07	0.53
Pinus sylvestris	Scots pine	0.00	0.00	0.15	0.18	0.17
Quercus prinus	chestnut oak	0.00	0.00	0.04	0.09	0.64
Carya ovata	shagbark hickory	0.00	0.00	0.03	0.05	0.21
Robinia pseudoacacia	black locust	0.00	0.00	0.02	0.03	0.08

Table 10A. Kenora Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	59.15	43.71	62.59	65.19	56.26
	Agriculture	3.69	3.32	30.72	65.87	79.39
Picea mariana	black spruce	14.31	8.91	3.24	0.62	0.10
Pinus banksiana	jack pine	7.85	3.23	2.75	0.99	0.42
Betula papyrifera	paper birch	3.11	3.72	2.07	1.16	0.87
Abies balsamea	balsam fir	2.61	5.53	1.49	0.40	0.11
Populus tremuloides	quaking aspen	1.45	10.57	5.92	4.60	3.40
Picea glauca	white spruce	1.22	1.27	0.78	0.23	0.20
Larix laricina	tamarack	1.16	3.20	1.20	0.53	0.33
Thuja occidentalis	northern white cedar	0.69	4.94	0.91	0.48	0.47
Pinus strobus	eastern white pine	0.34	1.04	0.55	0.77	0.81
Fraxinus nigra	black ash	0.34	3.22	1.50	1.39	1.08
Pinus resinosa	red pine	0.31	2.40	1.90	1.84	2.16
Populus balsamifera	balsam poplar	0.18	1.15	0.37	0.22	0.10
Fraxinus pennsylvanica	green ash	0.06	0.28	0.87	1.85	2.45
Fraxinus americana	white ash	0.05	0.01	0.07	0.09	0.39
Tilia americana	American basswood	0.01	0.82	1.82	2.44	3.19
Ulmus americana	American elm	0.01	0.20	0.48	1.05	2.09
Acer rubrum	red maple	0.01	1.86	0.86	1.37	2.16
Acer saccharum	sugar maple	0.01	0.84	0.95	0.91	1.76
Betula alleghaniensis	yellow birch	0.00	0.16	0.06	0.09	0.09
Acer saccharinum	silver maple	0.00	0.05	0.14	0.72	1.52
Populus grandidentata	bigtooth aspen	0.00	0.38	0.75	0.78	0.72
Quercus rubra	northern red oak	0.00	0.34	1.67	2.67	3.60
Tsuga canadensis	eastern hemlock	0.00	0.09	0.01	0.02	0.04
Prunus serotina	black cherry	0.00	0.06	0.07	0.29	0.82
Quercus velutina	black oak	0.00	0.01	0.02	0.28	0.53
Quercus alba	white oak	0.00	0.01	0.05	0.50	0.81
Pinus sylvestris	Scots pine	0.00	0.01	0.02	0.08	0.12
Populus deltoides	eastern cottonwood	0.00	0.00	0.03	0.16	0.79
Juniperus virginiana	eastern redcedar	0.00	0.00	0.04	0.20	0.59
Celtis occidentalis	hackberry	0.00	0.00	0.01	0.08	0.34
Carya cordiformis	bitternut hickory	0.00	0.00	0.00	0.04	0.30
Juglans nigra	black walnut	0.00	0.00	0.00	0.01	0.22

Table 11A. Mauricie Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	36.13	30.28	29.73	32.37	27.77
	Agriculture	0.52	0.39	3.42	7.09	10.48
Picea mariana	black spruce	17.13	13.67	4.78	1.19	0.21
Betula papyrifera	paper birch	11.08	13.27	7.30	3.14	1.76
Abies balsamea	balsam fir	6.51	7.64	11.33	7.02	3.94
Pinus banksiana	jack pine	5.67	4.36	1.23	0.31	0.10
Populus tremuloides	quaking aspen	5.39	5.75	4.03	2.52	1.56
Betula alleghaniensis	yellow birch	4.05	6.05	6.52	4.92	4.10
Acer saccharum	sugar maple	3.41	4.45	8.72	9.55	9.56
Picea glauca	white spruce	2.86	3.30	2.73	1.21	0.37
Acer rubrum	red maple	1.95	2.91	6.37	9.99	12.35
Thuja occidentalis	northern white cedar	1.72	2.72	3.93	2.24	1.32
Picea rubens	red spruce	0.67	1.04	3.61	3.26	2.91
Pinus strobus	eastern white pine	0.63	1.06	1.48	4.05	6.45
Larix laricina	tamarack	0.40	0.42	0.40	0.36	0.24
Fagus grandifolia	American beech	0.36	0.58	1.95	3.68	4.70
Populus grandidentata	bigtooth aspen	0.30	0.55	0.73	0.84	0.93
Tsuga canadensis	eastern hemlock	0.17	0.33	1.62	4.86	7.18
Picea abies	Norway spruce	0.17	0.15	0.09	0.34	0.51
Populus balsamifera	balsam poplar	0.15	0.15	0.23	0.16	0.08
Fraxinus nigra	black ash	0.08	0.14	0.22	0.24	0.24
Pinus resinosa	red pine	0.07	0.12	0.16	0.35	0.56
Tilia americana	American basswood	0.06	0.11	0.24	0.37	0.54
Quercus rubra	northern red oak	0.04	0.08	0.33	1.27	2.57
Fraxinus americana	white ash	0.02	0.03	0.47	1.64	2.81
Acer saccharinum	silver maple	0.01	0.02	0.06	0.07	0.06
Prunus serotina	black cherry	0.01	0.02	0.25	1.46	2.57
Fraxinus pennsylvanica	green ash	0.00	0.00	0.02	0.05	0.11
Quercus velutina	black oak	0.00	0.00	0.01	0.02	0.08
Ulmus americana	American elm	0.00	0.00	0.04	0.17	0.38
Pinus sylvestris	Scots pine	0.00	0.00	0.01	0.11	0.19
Quercus alba	white oak	0.00	0.00	0.01	0.05	0.15
Carya cordiformis	bitternut hickory	0.00	0.00	0.01	0.05	0.15
Carya ovata	shagbark hickory	0.00	0.00	0.00	0.02	0.06
Quercus prinus	chestnut oak	0.00	0.00	0.00	0.03	0.10

Table 12A. Paquia Porcupine Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	44.74	56.97	80.21	87.26	90.77
	Agriculture	12.87	38.86	63.56	77.71	80.33
Populus tremuloides	quaking aspen	20.11	29.09	13.90	8.05	5.03
Picea mariana	black spruce	17.97	5.24	0.70	0.12	0.10
Larix laricina	tamarack	6.13	1.96	0.41	0.06	0.04
Pinus banksiana	jack pine	4.71	1.24	0.39	0.10	0.08
Picea glauca	white spruce	3.05	2.06	0.40	0.15	0.12
Populus balsamifera	balsam poplar	2.09	2.33	0.97	0.54	0.39
Betula papyrifera	paper birch	0.76	0.32	0.18	0.08	0.05
Abies balsamea	balsam fir	0.20	0.08	0.13	0.03	0.04
Fraxinus nigra	black ash	0.04	0.03	0.20	0.16	0.09
Fraxinus americana	white ash	0.01	0.09	0.19	0.06	0.02
Ulmus americana	American elm	0.01	0.01	0.03	0.19	0.31
Fraxinus pennsylvanica	green ash	0.00	0.00	0.42	0.78	0.78
Pinus strobus	eastern white pine	0.00	0.00	0.05	0.01	0.01
Tilia americana	American basswood	0.00	0.00	0.00	0.06	0.14
Populus deltoides	eastern cottonwood	0.00	0.00	0.00	0.08	0.17

Table 13A. Peace River East Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	**Common name**	**1960s**	**1990s**	**2020s**	**2050s**	**2080s**
	Non-Forested	40.57	50.25	66.86	81.84	82.27
	Agriculture	13.73	49.87	50.60	63.05	61.61
Populus tremuloides	quaking aspen	25.77	35.54	24.66	12.09	10.80
Picea mariana	black spruce	14.85	4.26	2.72	0.61	0.46
Picea glauca	white spruce	6.71	3.62	1.88	0.47	0.30
Pinus banksiana	jack pine	5.00	0.83	0.61	0.28	0.25
Larix laricina	tamarack	2.90	0.86	0.91	0.19	0.19
Populus balsamifera	balsam poplar	2.03	2.77	1.70	0.83	0.65
Pinus contorta	lodgepole pine	0.58	0.75	0.06	0.01	0.00
Betula papyrifera	paper birch	0.55	0.41	0.27	0.28	0.33
Abies balsamea	balsam fir	0.08	0.03	0.06	0.25	0.29
Fraxinus nigra	black ash	0.00	0.00	0.01	0.18	0.28
Thuja occidentalis	northern white cedar	0.00	0.00	0.01	0.12	0.19
Fraxinus pennsylvanica	green ash	0.00	0.00	0.00	0.71	0.94
Acer rubrum	red maple	0.00	0.00	0.00	0.08	0.14
Pinus resinosa	red pine	0.00	0.00	0.00	0.06	0.17
Pinus strobus	eastern white pine	0.00	0.00	0.00	0.05	0.07
Acer saccharum	sugar maple	0.00	0.00	0.00	0.05	0.10
Tilia americana	American basswood	0.00	0.00	0.00	0.02	0.10
Quercus rubra	northern red oak	0.00	0.00	0.00	0.01	0.09
Populus grandidentata	bigtooth aspen	0.00	0.00	0.00	0.01	0.05

Table 14A. Pic Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	37.19	35.10	34.68	37.34	37.84
	Agriculture	0.23	0.07	1.89	2.28	2.78
Picea mariana	black spruce	27.72	23.32	12.81	4.26	1.57
Betula papyrifera	paper birch	8.81	11.60	11.37	6.89	4.72
Pinus banksiana	jack pine	5.77	6.60	4.98	1.36	0.92
Abies balsamea	balsam fir	4.00	4.42	4.90	5.68	4.34
Larix laricina	tamarack	1.94	1.57	0.81	0.53	0.51
Picea glauca	white spruce	1.86	2.46	2.91	2.33	1.89
Thuja occidentalis	northern white cedar	1.70	1.99	2.91	3.53	3.68
Populus tremuloides	quaking aspen	1.11	0.96	2.91	2.58	3.47
Betula alleghaniensis	yellow birch	0.29	0.64	3.83	4.26	3.40
Pinus strobus	eastern white pine	0.22	0.52	2.98	3.89	3.38
Acer saccharum	sugar maple	0.14	0.44	3.32	9.19	12.01
Acer saccharinum	silver maple	0.13	0.27	0.23	0.46	0.55
Acer rubrum	red maple	0.09	0.18	1.48	2.62	4.43
Populus balsamifera	balsam poplar	0.04	0.03	0.09	0.14	0.20
Pinus resinosa	red pine	0.02	0.08	0.53	0.69	1.12
Picea rubens	red spruce	0.02	0.03	0.29	1.07	0.33
Populus grandidentata	bigtooth aspen	0.01	0.02	0.74	1.11	1.13
Fraxinus nigra	black ash	0.01	0.02	0.15	0.48	0.98
Tsuga canadensis	eastern hemlock	0.00	0.02	0.49	1.57	2.22
Fagus grandifolia	American beech	0.00	0.01	0.37	1.27	1.12
Quercus rubra	northern red oak	0.00	0.01	0.37	1.69	2.20
Tilia americana	American basswood	0.00	0.00	0.08	0.52	1.15
Fraxinus americana	white ash	0.00	0.00	0.02	0.28	0.53
Prunus serotina	black cherry	0.00	0.00	0.01	0.10	0.25
Quercus alba	white oak	0.00	0.00	0.00	0.05	0.07
Fraxinus pennsylvanica	green ash	0.00	0.00	0.00	0.02	0.10
Ulmus americana	American elm	0.00	0.00	0.00	0.03	0.09

Table 15A. Quesnel Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	36.16	35.77	36.02	35.74	37.79
	Agriculture	0.65	0.53	0.83	1.12	1.19
Pinus contorta	lodgepole pine	14.02	10.65	10.04	7.63	5.36
Abies lasiocarpa	subalpine fir	9.31	9.13	6.69	3.93	2.82
Pseudotsuga menziesii	Douglas fir	7.15	7.94	11.91	16.84	15.70
Populus tremuloides	quaking aspen	5.49	4.58	4.19	1.88	0.93
Picea glauca	white spruce	5.02	4.03	2.95	0.57	0.13
Picea engelmannii	Engelmann spruce	2.37	2.43	3.23	3.70	2.97
Betula papyrifera	paper birch	1.86	1.79	1.59	1.06	0.72
Thuja plicata	western redcedar	1.59	2.64	4.11	6.35	6.28
Tsuga heterophylla	western hemlock	1.25	2.86	2.49	3.35	2.88
Populus balsamifera	balsam poplar	0.64	0.62	0.46	0.26	0.13
Picea mariana	black spruce	0.62	0.27	0.19	0.03	0.01
Larix occidentalis	western larch	0.27	0.33	1.56	3.52	3.56
Tsuga mertensiana	mountain hemlock	0.20	0.44	0.06	0.48	0.62
Pinus albicaulis	whitebark pine	0.19	0.22	0.30	0.33	0.18
Pinus monticola	western white pine	0.07	0.17	0.43	0.74	0.62
Abies balsamea	balsam fir	0.07	0.01	0.01	0.01	0.04
Abies amabilis	Pacific silver fir	0.04	0.15	0.09	0.17	0.16
Pinus ponderosa	ponderosa pine	0.01	0.02	0.38	1.13	1.64
Populus trichocarpa	black cottonwood	0.01	0.01	0.11	0.19	0.19
Pinus strobus	eastern white pine	0.00	0.01	0.02	0.02	0.22
Acer saccharum	sugar maple	0.00	0.00	0.01	0.02	1.53
Quercus rubra	northern red oak	0.00	0.00	0.01	0.02	0.36
Tsuga canadensis	eastern hemlock	0.00	0.00	0.01	0.01	0.41
Abies grandis	grand fir	0.00	0.03	0.45	3.58	5.94
Alnus rubra	red alder	0.00	0.01	0.04	0.17	0.17
Picea sitchensis	Sitka spruce	0.00	0.00	0.03	0.14	0.14
Acer rubrum	red maple	0.00	0.00	0.00	0.00	0.97
Betula alleghaniensis	yellow birch	0.00	0.00	0.00	0.00	0.29
Fraxinus americana	white ash	0.00	0.00	0.00	0.01	0.40
Tilia americana	American basswood	0.00	0.00	0.00	0.00	0.07
Fagus grandifolia	American beech	0.00	0.00	0.00	0.00	0.75
Picea rubens	red spruce	0.00	0.00	0.00	0.00	0.10
Prunus serotina	black cherry	0.00	0.00	0.00	0.00	0.27

Table 16A. Rouyn-Noranda Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	41.10	41.67	39.27	33.76	33.75
	Agriculture	1.76	3.21	7.04	11.60	15.69
Picea mariana	black spruce	25.62	19.41	6.44	1.97	0.54
Betula papyrifera	paper birch	6.42	7.66	8.12	4.20	2.06
Pinus banksiana	jack pine	4.62	4.51	1.99	0.36	0.21
Abies balsamea	balsam fir	4.07	4.23	5.42	8.01	3.23
Populus tremuloides	quaking aspen	2.82	3.45	4.11	3.09	2.60
Larix laricina	tamarack	1.91	1.32	0.51	0.45	0.26
Picea glauca	white spruce	1.68	2.14	2.50	2.00	0.83
Thuja occidentalis	northern white cedar	1.54	1.86	3.48	5.20	2.50
Betula alleghaniensis	yellow birch	1.43	2.11	4.95	4.75	3.43
Acer saccharum	sugar maple	1.09	2.13	7.04	10.63	10.87
Pinus strobus	eastern white pine	0.96	1.08	2.79	2.90	4.63
Acer rubrum	red maple	0.59	0.97	3.21	6.36	9.64
Populus grandidentata	bigtooth aspen	0.26	0.44	1.19	1.20	1.19
Pinus resinosa	red pine	0.16	0.18	0.44	0.48	0.60
Tsuga canadensis	eastern hemlock	0.16	0.27	1.16	2.47	5.22
Picea rubens	red spruce	0.14	0.22	0.88	2.49	1.14
Fagus grandifolia	American beech	0.12	0.31	1.04	1.75	2.75
Quercus rubra	northern red oak	0.12	0.16	0.68	1.15	1.98
Populus balsamifera	balsam poplar	0.08	0.10	0.20	0.36	0.15
Fraxinus nigra	black ash	0.05	0.11	0.38	0.62	0.57
Acer saccharinum	silver maple	0.05	0.10	0.17	0.10	0.15
Tilia americana	American basswood	0.03	0.08	0.41	0.85	1.18
Picea abies	Norway spruce	0.03	0.03	0.02	0.12	0.41
Fraxinus americana	white ash	0.01	0.02	0.17	0.86	2.58
Prunus serotina	black cherry	0.00	0.01	0.07	0.50	1.70
Quercus alba	white oak	0.00	0.00	0.01	0.05	0.17
Fraxinus pennsylvanica	green ash	0.00	0.00	0.02	0.08	0.21
Ulmus americana	American elm	0.00	0.00	0.02	0.20	0.66
Carya cordiformis	bitternut hickory	0.00	0.00	0.00	0.06	0.22
Quercus velutina	black oak	0.00	0.00	0.01	0.03	0.08
Pinus sylvestris	Scots pine	0.00	0.00	0.00	0.05	0.21
Juniperus virginiana	eastern redcedar	0.00	0.00	0.00	0.01	0.05
Carya ovata	shagbark hickory	0.00	0.00	0.00	0.02	0.10
Robinia pseudoacacia	black locust	0.00	0.00	0.00	0.01	0.06
Quercus prinus	chestnut oak	0.00	0.00	0.00	0.01	0.09

Table 17A. Spanish Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	31.56	32.01	34.63	32.64	26.39
	Agriculture	0.11	0.70	1.28	4.26	13.21
Picea mariana	black spruce	15.41	11.36	4.93	1.08	0.32
Betula papyrifera	paper birch	11.25	8.93	6.07	3.55	1.90
Abies balsamea	balsam fir	6.73	10.05	9.21	3.95	2.80
Pinus banksiana	jack pine	5.54	4.30	1.55	0.55	0.12
Thuja occidentalis	northern white cedar	3.72	4.51	5.07	3.27	2.06
Picea glauca	white spruce	2.96	2.81	2.47	1.36	0.51
Betula alleghaniensis	yellow birch	2.94	2.95	3.70	3.39	3.13
Acer saccharum	sugar maple	2.46	3.56	8.37	11.99	10.74
Pinus strobus	eastern white pine	2.31	2.23	3.17	4.83	6.57
Populus tremuloides	quaking aspen	1.95	1.51	2.36	2.52	1.86
Acer rubrum	red maple	1.24	2.15	3.05	7.02	10.97
Picea rubens	red spruce	1.12	3.06	2.70	1.16	1.93
Larix laricina	tamarack	1.10	0.89	0.55	0.43	0.28
Populus grandidentata	bigtooth aspen	0.43	0.34	0.79	0.86	0.94
Pinus resinosa	red pine	0.40	0.39	0.66	0.95	0.90
Tsuga canadensis	eastern hemlock	0.32	0.33	1.25	4.22	6.78
Acer saccharinum	silver maple	0.26	0.23	0.36	0.39	0.17
Fagus grandifolia	American beech	0.26	0.65	1.05	2.29	3.86
Quercus rubra	northern red oak	0.25	0.26	1.23	2.38	2.80
Populus balsamifera	balsam poplar	0.13	0.22	0.29	0.14	0.07
Fraxinus nigra	black ash	0.11	0.13	0.51	0.78	0.53
Tilia americana	American basswood	0.05	0.04	0.52	1.10	1.10
Fraxinus americana	white ash	0.02	0.04	0.22	1.37	3.03
Prunus serotina	black cherry	0.01	0.01	0.10	1.15	2.45
Picea abies	Norway spruce	0.00	0.00	0.00	0.31	0.66
Fraxinus pennsylvanica	green ash	0.00	0.00	0.02	0.12	0.21
Quercus alba	white oak	0.00	0.00	0.03	0.10	0.24
Ulmus americana	American elm	0.00	0.00	0.03	0.32	0.66
Pinus sylvestris	Scots pine	0.00	0.00	0.01	0.12	0.26
Carya cordiformis	bitternut hickory	0.00	0.00	0.01	0.09	0.24
Quercus velutina	black oak	0.00	0.00	0.00	0.03	0.11
Quercus prinus	chestnut oak	0.00	0.00	0.00	0.03	0.13
Carya ovata	shagbark hickory	0.00	0.00	0.00	0.03	0.12
Robinia pseudoacacia	black locust	0.00	0.00	0.00	0.03	0.08

Table 18A. Sundre Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	33.59	32.93	37.80	54.79	68.07
	Agriculture	3.11	1.95	10.22	14.13	13.08
Pinus contorta	lodgepole pine	28.31	27.56	24.43	9.73	2.81
Picea glauca	white spruce	9.45	9.60	9.05	5.32	2.28
Populus tremuloides	quaking aspen	9.10	9.15	10.36	9.26	5.35
Picea mariana	black spruce	7.57	8.85	8.63	5.22	0.73
Picea engelmannii	Engelmann spruce	3.78	3.44	2.37	1.20	1.06
Populus balsamifera	balsam poplar	1.34	1.33	1.64	1.43	0.80
Abies lasiocarpa	subalpine fir	1.30	1.60	0.79	0.58	0.56
Pseudotsuga menziesii	Douglas fir	0.55	0.48	0.39	2.11	4.35
Larix laricina	tamarack	0.55	0.52	0.78	0.63	0.14
Abies balsamea	balsam fir	0.53	0.93	0.45	0.20	0.00
Betula papyrifera	paper birch	0.24	0.22	0.26	0.31	0.22
Larix occidentalis	western larch	0.13	0.11	0.10	0.17	0.20
Pinus albicaulis	whitebark pine	0.11	0.07	0.08	0.14	0.11
Thuja plicata	western redcedar	0.01	0.02	0.01	0.01	0.07
Pinus ponderosa	ponderosa pine	0.00	0.00	0.00	6.36	11.17
Abies grandis	grand fir	0.00	0.00	0.00	0.01	0.26

Table 19A. Temagami Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	30.65	28.56	36.71	28.84	25.67
	Agriculture	0.38	0.40	1.80	6.40	18.94
Picea mariana	black spruce	12.24	6.63	3.06	0.55	0.06
Betula papyrifera	paper birch	10.60	7.05	4.97	2.53	1.31
Abies balsamea	balsam fir	8.27	14.22	7.61	3.47	2.26
Thuja occidentalis	northern white cedar	4.56	6.37	4.78	2.79	1.22
Pinus banksiana	jack pine	4.36	2.08	0.82	0.19	0.02
Betula alleghaniensis	yellow birch	3.94	4.62	3.48	3.35	3.06
Acer saccharum	sugar maple	3.50	5.75	10.40	11.70	9.73
Picea glauca	white spruce	3.04	2.79	2.23	0.86	0.16
Pinus strobus	eastern white pine	3.04	2.73	3.31	5.96	7.09
Populus tremuloides	quaking aspen	2.43	1.85	2.04	1.85	1.54
Picea rubens	red spruce	1.95	5.43	2.11	1.84	2.21
Acer rubrum	red maple	1.83	3.70	3.30	9.32	12.47
Larix laricina	tamarack	0.80	0.51	0.55	0.33	0.19
Populus grandidentata	bigtooth aspen	0.67	0.56	0.76	0.73	1.03
Pinus resinosa	red pine	0.50	0.40	0.70	0.77	0.70
Tsuga canadensis	eastern hemlock	0.49	0.51	1.72	5.89	7.55
Fagus grandifolia	American beech	0.43	1.14	1.14	3.28	4.63
Quercus rubra	northern red oak	0.37	0.36	1.79	2.57	2.75
Acer saccharinum	silver maple	0.22	0.13	0.53	0.25	0.09
Populus balsamifera	balsam poplar	0.19	0.36	0.24	0.10	0.05
Fraxinus nigra	black ash	0.16	0.18	0.63	0.62	0.32
Tilia americana	American basswood	0.08	0.08	0.77	1.09	0.93
Fraxinus americana	white ash	0.022	0.073	0.359	2.139	3.819
Prunus serotina	black cherry	0.01	0.02	0.16	1.89	3.02
Picea abies	Norway spruce	0.00	0.00	0.00	0.57	0.76
Fraxinus pennsylvanica	green ash	0.00	0.00	0.03	0.15	0.22
Ulmus americana	American elm	0.00	0.00	0.05	0.53	0.74
Quercus alba	white oak	0.00	0.00	0.05	0.13	0.28
Pinus sylvestris	Scots pine	0.00	0.00	0.01	0.20	0.32
Carya cordiformis	bitternut hickory	0.00	0.00	0.01	0.16	0.29
Quercus velutina	black oak	0.00	0.00	0.00	0.05	0.15
Juniperus virginiana	eastern redcedar	0.00	0.00	0.00	0.02	0.06
Quercus prinus	chestnut oak	0.00	0.00	0.00	0.05	0.21
Carya ovata	shagbark hickory	0	0	0	0.049	0.178
Robinia pseudoacacia	black locust	0	0	0	0.047	0.102

Table 20A. Wabigoon Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	50.16	45.06	53.99	55.77	49.01
	Agriculture	1.30	2.21	16.47	51.49	69.85
Picea mariana	black spruce	20.80	11.09	5.58	1.43	0.22
Pinus banksiana	jack pine	9.36	5.00	3.38	1.46	0.53
Betula papyrifera	paper birch	3.89	4.66	3.08	1.73	1.21
Abies balsamea	balsam fir	3.15	5.61	3.06	0.96	0.25
Picea glauca	white spruce	1.22	1.36	1.03	0.39	0.24
Larix laricina	tamarack	1.14	2.16	1.54	0.85	0.50
Thuja occidentalis	northern white cedar	0.66	3.59	2.21	1.06	0.64
Populus tremuloides	quaking aspen	0.51	7.84	7.41	6.10	4.57
Pinus strobus	eastern white pine	0.45	1.08	0.81	1.02	1.08
Pinus resinosa	red pine	0.36	1.95	2.11	2.36	2.56
Fraxinus nigra	black ash	0.23	2.19	2.14	2.09	1.52
Acer rubrum	red maple	0.06	1.57	1.47	2.27	2.88
Populus balsamifera	balsam poplar	0.04	0.73	0.58	0.32	0.15
Fraxinus americana	white ash	0.03	0.01	0.05	0.15	0.46
Fraxinus pennsylvanica	green ash	0.02	0.15	0.60	1.76	2.49
Acer saccharum	sugar maple	0.02	0.71	1.05	1.34	2.16
Betula alleghaniensis	yellow birch	0.01	0.17	0.11	0.14	0.12
Populus grandidentata	bigtooth aspen	0.01	0.29	0.72	1.06	0.98
Tsuga canadensis	eastern hemlock	0.01	0.08	0.04	0.05	0.05
Quercus rubra	northern red oak	0.00	0.22	1.39	3.26	4.35
Prunus serotina	black cherry	0.00	0.05	0.06	0.32	0.91
Acer saccharinum	silver maple	0.00	0.03	0.08	0.68	1.43
Tilia americana	American basswood	0.00	0.49	1.49	2.67	3.63
Ulmus americana	American elm	0.00	0.11	0.35	1.05	2.20
Quercus velutina	black oak	0.00	0.01	0.01	0.34	0.63
Quercus alba	white oak	0.00	0.00	0.02	0.69	1.12
Pinus sylvestris	Scots pine	0.00	0.00	0.01	0.08	0.13
Juniperus virginiana	eastern redcedar	0.00	0.00	0.02	0.18	0.58
Populus deltoides	eastern cottonwood	0.00	0.00	0.01	0.13	0.71
Celtis occidentalis	hackberry	0.00	0.00	0.00	0.06	0.29
Carya cordiformis	bitternut hickory	0.00	0.00	0.00	0.08	0.34
Robinia pseudoacacia	black locust	0.00	0.00	0.00	0.04	0.06
Juglans nigra	black walnut	0.00	0.00	0.00	0.01	0.23
Carya ovata	shagbark hickory	0.00	0.00	0.00	0.00	0.08

Table 21A. Western Nova Scotia Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	26.87	24.62	30.25	39.53	44.58
	Agriculture	1.25	1.17	9.64	36.66	45.38
Picea rubens	red spruce	18.30	20.89	14.20	0.01	0.01
Acer rubrum	red maple	13.78	14.51	13.65	9.89	8.79
Abies balsamea	balsam fir	11.57	10.76	6.90	0.00	0.00
Picea mariana	black spruce	8.97	8.55	6.89	0.00	0.00
Pinus strobus	eastern white pine	3.78	4.94	5.99	4.76	3.50
Picea glauca	white spruce	3.06	2.69	2.50	0.01	0.01
Larix laricina	tamarack	2.82	2.85	2.22	0.06	0.01
Betula papyrifera	paper birch	2.71	2.62	2.42	0.11	0.07
Acer saccharum	sugar maple	2.69	2.35	1.69	1.69	1.23
Betula alleghaniensis	yellow birch	2.35	2.02	1.19	0.56	0.46
Fagus grandifolia	American beech	0.64	0.59	0.54	0.65	0.58
Tsuga canadensis	eastern hemlock	0.37	0.51	1.19	1.19	0.38
Pinus resinosa	red pine	0.37	0.37	0.20	0.27	0.12
Quercus rubra	northern red oak	0.34	0.42	1.44	5.35	3.44
Populus tremuloides	quaking aspen	0.13	0.13	0.38	0.14	0.19
Fraxinus americana	white ash	0.03	0.04	0.34	1.84	2.33
Thuja occidentalis	northern white cedar	0.02	0.05	0.06	0.01	0.02
Picea abies	Norway spruce	0.01	0.01	0.02	0.07	0.04
Populus grandidentata	bigtooth aspen	0.00	0.01	0.09	0.34	0.24
Alnus rubra	red alder	0.00	0.00	0.37	0.79	0.65
Tsuga heterophylla	western hemlock	0.00	0.00	0.57	0.75	0.54
Prunus serotina	black cherry	0.00	0.01	0.20	1.17	1.09
Quercus velutina	black oak	0.00	0.00	0.48	3.29	3.03
Quercus alba	white oak	0.00	0.00	0.43	3.43	3.24
Ulmus americana	American elm	0.00	0.00	0.05	0.28	0.35
Tilia americana	American basswood	0.00	0.00	0.03	0.16	0.11
Pinus sylvestris	Scots pine	0.00	0.00	0.01	0.04	0.08
Pseudotsuga menziesii	Douglas fir	0.00	0.00	1.94	4.88	4.23
Thuja plicata	western redcedar	0.00	0.00	0.41	0.68	0.51
Quercus coccinea	scarlet oak	0.00	0.00	0.28	2.66	3.32
Quercus prinus	chestnut oak	0.00	0.00	0.17	2.72	1.48
Acer macrophyllum	bigleaf maple	0.00	0.00	0.17	0.56	0.47
Populus trichocarpa	black cottonwood	0.00	0.00	0.07	0.11	0.08
Carya ovata	shagbark hickory	0.00	0.00	0.05	0.46	0.42
Liriodendron tulipifera	yellow poplar	0.00	0.00	0.05	1.90	1.68
Abies amabilis	Pacific silver fir	0.00	0.00	0.05	0.04	0.02

Juniperus virginiana	eastern redcedar	0.00	0.00	0.03	0.33	0.70
Robinia pseudoacacia	black locust	0.00	0.00	0.02	0.29	0.30
Fraxinus pennsylvanica	green ash	0.00	0.00	0.02	0.22	0.22
Carya cordiformis	bitternut hickory	0.00	0.00	0.02	0.14	0.10
Acer saccharinum	silver maple	0.00	0.00	0.01	0.23	0.16
Picea sitchensis	Sitka spruce	0.00	0.00	0.01	0.03	0.02
Juglans nigra	black walnut	0.00	0.00	0.01	0.29	0.27
Quercus palustris	pin oak	0.00	0.00	0.01	0.14	1.28
Chamaecyparis thyoides	Atlantic white cedar	0.00	0.00	0.01	0.11	0.18
Populus deltoides	eastern cottonwood	0.00	0.00	0.01	0.05	0.05
Abies grandis	grand fir	0.00	0.00	0.00	0.02	0.02
Pinus virginiana	Virginia pine	0.00	0.00	0.00	0.05	0.04
Liquidambar styraciflua	sweetgum	0.00	0.00	0.00	0.03	0.27
Quercus stellata	post oak	0.00	0.00	0.00	0.02	0.05

Table 22A. White River Modeled climatic habitat for species for five consecutive 30-year climate normal periods, including two historic periods (1960s and 1990s) and three future periods (2020s, 2050s, and 2080s). Species values represent an estimated proportion of the land base, assuming no human disturbance. An estimated percent of climate conditions climate conditions suitable for cropland or rangeland use, are provided as well as climate conditions not supporting forested ecosystems

Scientific name	Common name	1960s	1990s	2020s	2050s	2080s
	Non-Forested	36.68	33.99	32.50	37.31	33.42
	Agriculture	0.25	0.08	1.26	2.81	2.47
Picea mariana	black spruce	26.88	21.78	10.47	3.70	1.15
Betula papyrifera	paper birch	9.26	12.10	9.38	6.07	4.15
Pinus banksiana	jack pine	5.90	6.32	3.88	1.19	0.65
Abies balsamea	balsam fir	4.06	4.69	9.16	5.74	4.24
Picea glauca	white spruce	1.99	2.61	2.80	2.06	1.43
Larix laricina	tamarack	1.89	1.53	0.69	0.50	0.43
Thuja occidentalis	northern white cedar	1.76	2.19	4.53	3.30	2.89
Populus tremuloides	quaking aspen	1.13	1.01	2.27	2.23	2.60
Betula alleghaniensis	yellow birch	0.35	1.21	3.83	3.92	3.67
Pinus strobus	eastern white pine	0.30	0.61	2.68	4.14	4.85
Acer saccharum	sugar maple	0.22	1.44	3.78	8.85	11.37
Acer saccharinum	silver maple	0.17	0.44	0.19	0.44	0.44
Acer rubrum	red maple	0.10	0.23	2.40	3.61	6.46
Pinus resinosa	red pine	0.05	0.10	0.45	0.65	0.90
Populus balsamifera	balsam poplar	0.04	0.03	0.19	0.14	0.15
Picea rubens	red spruce	0.02	0.05	2.97	1.56	1.40
Populus grandidentata	bigtooth aspen	0.01	0.03	0.52	0.92	0.93
Fraxinus nigra	black ash	0.01	0.02	0.16	0.46	0.73
Tsuga canadensis	eastern hemlock	0.01	0.07	0.41	2.26	4.25
Picea abies	Norway spruce	0.01	0.01	0.00	0.03	0.15
Fagus grandifolia	American beech	0.01	0.04	0.63	1.62	2.51
Quercus rubra	northern red oak	0.00	0.04	0.30	1.78	2.62
Tilia americana	American basswood	0.00	0.01	0.06	0.46	0.87
Fraxinus americana	white ash	0.00	0.01	0.05	0.59	1.12
Prunus serotina	black cherry	0.00	0.00	0.01	0.28	0.79
Quercus alba	white oak	0.00	0.00	0.00	0.06	0.08
Fraxinus pennsylvanica	green ash	0.00	0.00	0.00	0.02	0.08
Ulmus americana	American elm	0.00	0.00	0.00	0.05	0.12