GROWTH AND SURVIVAL OF BLACK SPRUCE POPULATIONS IN AN ASSISTED MIGRATION TRIAL NEAR THUNDER BAY, ONTARIO

by

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April 28, 2023

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An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Honours Bachelor of Science in Forestry

Faculty of Natural Resource Management
Lakehead University

April 28, 2023

Major Advisor	Second Reader

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ABSTRACT

Milani, J. E. 2023. Growth and survival of black spruce populations in an assisted migration trial near Thunder Bay, Ontario. 41 pp

Keywords: provenance data, climate change, forest management adaptation, black spruce, seed sources, reforestation, growth, survival.

This study examined the height growth and survival responses of selected 16 black spruce (*Picea mariana* (Mill.)) seed sources originating from across Ontario, Quebec, Minnesota, Wisconsin, and Michigan in an assisted migration trial located near Thunder Bay, Ontario. Survival and growth responses varied significantly among the black spruce seed sources growing at the test site. Seed sources originating from northern Minnesota had a greater survival and mean productivity index when compared to Ontario seed sources, excluding the seed source from the Algoma forest which had the highest survival percentage and productivity index among all seed sources. The local seed source originating from the Lakehead forest performed below average for both survival and productivity index, suggesting that local seed sources may not be the best suited for planting in future climatic scenarios for this region. Climate variables identified as significant predictors of black spruce growth and survival included mean annual temperature, mean summer precipitation, and frost-free period. This study further supports the hypothesis that southern seed sources may be better suited for the future reforestation of northern regions. The identification of adapted seed sources to areas of optimum growth and survival will assist reforestation programmes under changing climate scenarios highlighting adaptative patterns of variation. Through the identification of adapted seed sources, the risk of maladapted sources will be reduced providing managers with a better understanding of the importance of assisted migration measures.

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ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor Dr. Ashley Thomson for her patience and contributions throughout the thesis process. I would like to thank Mr. Paul Charrette for serving as my second reader for my thesis and assisting in the tree-measuring portion of the data collection. Additionally, I would like to thank Dylan Cole for assisting in the tree-measuring portion of the data collection. Finally, I would like to thank my partner Ashlyn Kopanski for her consistent support throughout the school year and life.

INTRODUCTION

Climate change is the primary force affecting species composition and vegetation within a given area (Davis 1989; Rizzo and Wiken 1992). Climatic changes to both temperature and precipitation will have direct impacts on the management of forests across the globe. With the heightened focus on sustainable forest practices and maintaining ecological functions, forest managers will be expected to adapt to the changing climate. In Canada, General Circulation Models (GCMs) have forecasted a 1.5 °C to 4.2°C annual temperature increases by 2040, 4.5°C to 7.5°C by 2070; and 7.0°C to 10.3°C by 2100 (McKenney *et al*. 2009). On the other hand, precipitation is projected to be more varied throughout regions but with an overall projection of an increase of 20% to 30% by 2100.

Climate change is expected to affect plant growth and survival, as the current habitats where the species are located may no longer provide suitable conditions for future growth and regeneration (Papadopol 2000). Tree species have a natural phenotypic plasticity that may allow them to survive and adapt to the changing climate, however, there is a limitation to that adaptational ability, and population extirpation is a real possibility due to the rapid rate of climatic change (Peters 1990; Nelson *et al*. 2005). Due to the long rotation periods of trees and their naturally slow migration rates, the utilization of seed sources adapted to plausible future climates is significant for the planned adaptation in reforestation. ‘Acclimation’ and ‘adaptation’ are two major biological strategies that are considered important for species' successful persistence under climate change (Alberto *et al*. 2013). Acclimation is the progression by which an individual organism alters to changes in the environment during its lifetime through phenotypic plasticity, while adaptation is a long-term evolutionary process by which the population adjusts to variations in the environment over several generations (Li *et al.* 2020). Seed sources selected for adaptability and survival to transplanted locations for reforestation purposes are essential for the conservation of genetic variation of tree species while also minimizing the risk of tree maladaptation. The geographical range of seed source transplantation through assisted migration is actively being researched to assist forest managers with response to climate change.

Assisted migration can be defined as the movement of a species and population to aid in the natural range expansion in direct response to climate change (Peters and Darling, 1985). Long-lived species such as trees will be faced with difficulties compared to short-lived species due to their inability to adapt and track suitable climate conditions (Jump and Penueles, 2005). Davis and Shaw (2001) propose that current climate projections require plants to annually migrate three to five thousand meters, which greatly exceeds the current observed rates of less than 500 meters of annual range expansion. For trees, it is likely to take multiple generations for a population to become adapted through changes in allele frequencies (Beaulieu and Rainville, 2005). The discrepancy between the rate at which trees can respond to climate change through molecular evolution compared to the rapid rate of anthropogenic warming will likely have serious impacts on forest growth and regeneration (McKenney *et al.* 2009).

A black spruce provenance study conducted by Thomson *et al*. (2009) concluded that seed sources from northern latitudes would benefit from increased temperatures leading directly to increased height growth. Additionally, the study concluded that seed sources in central and southern regions of the species range were performing at or near the maximum level of growth, leading the researchers to conclude that the seed sources will likely suffer with any increase in temperature (Thomson *et al*. 2009). To achieve superior height growth performance in response to predicted future climates, the establishment of southern black spruce seed sources in northern forests will be needed (Thomson *et al*. 2009). The study suggests that the best-matched seed sources for future temperatures for most southern areas were nonexistent for the current geographical range of black spruce (Thomson *et al*. 2009). The authors concluded that the optimal habitat for the black spruce provenances within the study is anticipated to shift northward by 2 degrees as a direct result of climate change, although in northwestern Ontario, that shift is anticipated to be 3 and 4 degrees for areas situated around the north and northwest shores of Lake Superior (Thomson *et al*. 2009).

A black spruce provenance study conducted by Morgenstern and Mullin (1990) examined the height and survival of seed sources from the Atlantic Coast to Alberta in relation to geographic and climatic variables. Summer precipitation, last spring frost, frost-free period, degree days, the start of the growing season, and the length of the growing season were the variables utilized within the study. The researchers determined there is a positive correlation between height and survival for seed sources originating from temperate regions such as southern Quebec and Ontario, and Great Lake States. The study further supports the general principle of provenance variation that increased height growth is correlated with the northern migration of southern seed sources. Survival responded differently compared to height with northern seed sources demonstrating an increased survival at southern latitudes compared to northern planting locations. This study, in addition to studies conducted by Dietrichson (1964) and Eriksson *et al*. (1980), supports the hypothesis that the movement of seed sources is a necessary management approach for optimal seed source performance. An acknowledged shortcoming of the study is the lack of discussion concerning climate change suggesting that conclusions in the study are likely too conservative and greater northward movement may be possibly expected.

A recently published study, conducted by Pedlar *et al.* (2021), examined the growth and survival responses of northern populations of black spruce and jack pine to southward seed transfers. Unlike the study conducted by Morgenstern and Mullin, this study provided valuable insight into potential future climate change responses for black spruce and jack pine. The researchers concluded that peak growth was associated with seed transfers to warmer annual climates from northern colder populations. However, survival responses for both species exhibited poorer survival rates when relocated to warmer and drier environments occurring in the southern region. These findings suggest that under warmer and drier future climate change conditions for northern Canadian forests, reduced survival is to be expected for northern populations. Conversely, the surviving trees are likely to grow at an increased rate until a certain degree of climate warming has occurred.

The objective of this thesis is to evaluate the growth and survival of black spruce in an assisted migration trial near Thunder Bay, Ontario. The findings of this report will assist the management and reforestation of black spruce throughout its eastern range in response to climate change. Based on other similar studies of black spruce, I expect that southern seed sources will outperform local seed sources at the Thunder Bay test site. I anticipate the results from the analysis will provide useful insight into how sensitive black spruce is to changes in climate and help identify provenances better adapted to climate change in the northwestern Ontario region.

LITERATURE REVIEW

BLACK SPRUCE ECOLOGY AND SILVICS

Black Spruce (*Picea mariana*) is one of the most important tree species in the North American boreal forest due to its wide distribution and its commercial value. The species forms extensive forests throughout the boreal zone extending from western North America in Alaska to Eastern North America in Newfoundland (Hoise 1967). Furthermore, the species can form scattered forest patches and small groves towards the treeline in the northern extent of its range. Regeneration of black spruce occurs naturally following disturbances such as clearcutting or a fire and black spruce establishment after fire is abundant and relatively fast due to its semi-serotinous cones and suitable seedbeds (Rowe 1984; DesRochers and Gagnon 1997). Black spruce can grow in a variety of local sites, including wet organic, deep humus, loams, clays, sands, coarse till, and shallow soil mantles over bedrock (Viereck and Johnston 1990). Black spruce is associated with a variety of species but typically is not tolerant as a climax species. It usually forms pure stands on shallow, poorly drained sites with cold soils where competitors are limited due to the bleakness of the site (Morgenstern 1978).

ADAPTIVE VARIATION WITHIN BLACK SPRUCE SPECIES

Black spruce is essentially an undomesticated tree species that is an ecologically important tree of the North American boreal biome. It is characterized by a large historical population size, wind pollination and an outcrossed mating system, which is associated with high migration rates and genetic diversity (Prunier *et al*. 2012). Like most boreal forest species, black spruce is adapted to harsh winter environments but is expected to experience warmer conditions with the changing climate (McKenney *et al*.

2007). Thomson *et al*. (2009) suggest that within a species, populations may differ in their response to climate, the habitats that they can occupy, and in the extent of suitable habitat for optimal survival and growth. The range of environmental conditions covered by the wide geographical distributions of many boreal and temperate trees can encourage the formation of populations that are adaptively genetically diverged at regional scales (Rossi, 2015). Rehfeldt *et al*. (1999) suggest that a major redistribution of tree species and genotypes across the landscape may be needed to maintain forest health, productivity, and biodiversity should predicted climate change scenarios take place.

Temperature is the predominant factor driving clinal variation in black spruce bud break across the species range (Rossi, 2015). The timing of budset in black spruce is strongly correlated to the latitude of origin and temperature, with an earlier budset associated with stronger cold resistance within the species (Prunier *et al*. 2011). Rossi (2015) concluded that the clinal variation of bud break of black spruce suggests that local populations retain plasticity in response to warming treatments and thus can be utilized for appropriate seed transfer within the species' established geographical range. In plants and trees, cold resistance can originate from various physiological and phenological changes such as growth cessation, budset, photosynthetic decrease and metabolite accumulation (Guy, 1990).

CLIMATE CHANGE AND BOREAL FOREST TREE SPECIES

Concern over the potential negative effects of increased temperatures on tree growth has spurred research aimed at understanding the response of tree populations to climate change (Aitken *et al*. 2007). The boreal forest faces significant risk due to a changing climate, including heightened frequency of wildfires (Flannigan and Wagner 1991; Stocks *et al*. 1998), pest outbreaks and drought (Kurz *et al*. 2008), large-scale shifting of forest vegetation (Rizzo and Wilken 1992), and species maladaptation (Schmidtling 1994; Rehfeldt *et al.* 2006).Tree populations have three possible fates in a rapidly changing environment; persistence through migration, persistence through adaptation to a change in current local conditions, and extirpation (Aitken *et al*. 2008). Contemporary changes in our atmosphere have directly caused global mean temperatures to increase at rates that have not been previously experienced in recent geologic time, such that plants can not adapt or migrate fast enough to the rapidly changing climate.

Natural populations of forest trees typically have high levels of genetic variation within the population due to the commonly large effective population sizes and outcrossing mating systems (Hamrick *et al*. 1992). Consequently, there naturally occurs a wide variety of different genotypes where natural selection can act to confer more resistance or tolerance to drought stress, pest outbreaks, or high temperatures in subsequent generations (Sáenz-Romero *et al*. 2021). However, if the adaptation does not occur rapidly enough, coinciding with climatic changes, then the average fitness of individuals or the overall size of the population may drop too low for recovery through evolutionary rescue and adaptation (Gonzalez *et al*. 2012).

There is strong evidence suggesting that species migration will experience an adaptive lag with current climatic migration (Aitken *et al*. 2008; Rehfeldt *et al*. 2006). As such, species migrated distances will have to be small enough for good survival not just at the establishment but in the long term to ensure adaptation toward the end of the rotation. Assisted migration continues to be proposed as an important climate change adaptation strategy for reforestation approaches with further development of protocols for species movement being incorporated into policies across Canada.

It is uncertain to what extent individual tree species populations were able to naturally migrate with shifts in suitable climatic zones (Price *et al*. 2013) based on paleobotanical studies by Clark (1998). More recently, Aitken *et al*. (2008) reported that maximum postglacial migration rates in Canadian tree populations were of the order of 10 kilometres per century. McLachlan *et al*. (2005) determined that postglacial species migration rates of 10 kilometres per century, later reported by Aitken *et al*. (2008), were theoretically possible, but most boreal species were likely to spread at a much slower rate. It is then theorized that due to the 10-kilometre per century maximum tree species colonization rate, boreal species will be unable to spread fast enough to match the rate of climate change that is implied in most GCM projections (Loarie *et al*. 2009)

PORTFOLIO THEORY GUIDANCE FOR REFORESTATION IN RESPONSE TO CLIMATE CHANGE

The response of forests to the projected global climate change is expected to be overwhelmingly difficult (Crowe and Parker 2008). Due to the climate being the primary force that determines the vegetation of a given region, the likelihood of large shifts in the distribution and overall productivity of tree species can be forecasted utilizing climate change scenarios of general circulation models (GCMs) as predictors (Iverson and Prasad 2001). Due to the magnitude and rate of projected climate change forecasts, paired with the long-rotational time of tree species, the future survival of boreal species may be threatened in the near future. Difficulties for planned adaptation to climate change come down to the uncertainty of estimated changes in climate parameters due to the complexity of scientists making definitive predictions. A modern portfolio theory is described as a method of portfolio management to reduce risk, which can be traced to Harry Markowitz's 1952 paper titled "Portfolio Selection" (Markowitz 1952). The theory indicates that given a desired level of risk, an investor can therefore optimize the expected returns of a portfolio through diversification.

Crowe and Parker (2008) established a portfolio theory for the selection of multiple sources of white spruce for reforestation under future climate uncertainties. Within their study, the researchers demonstrated that seed sources are not selected to perform equally across all possible future scenarios but rather the sources are selected to specialize in equally probable climate change scenarios. The primary principle of the portfolio theory model is the selection of seed sources for reforestation purposes that collectively reduce the likelihood of maladaptation and increase the return under future climate uncertainties. The utilization of a portfolio theory in Crowe and Parker's (2008) study demonstrates the decision-making in planned adaptation to climate change for reforestation purposes.

PROVENANCE TRIALS AND GENETIC ADAPTATION

Plant species typically exhibit spatial structuring of genetic variation throughout their geographical range (O'Brien *et al.* 2007). Therefore the preservation of genetic variation within a species in restoration programmes should be a priority moving forward. An assessment of a species' adaptive variation within its geographical range requires the measurement of heritable traits of plants from different source populations and the establishment of a shared site for environment control through a provenance trial (Crandall *et al.* 2000; Mckay *et al.* 2005). Field experiments using provenance trials showcase differences in survival and thus require a long test period (Campbell 1974).

Provenance trials have been routinely utilized in forestry since the early 19th century for the detection of economically desirable characteristics in targeted tree populations for tree-breeding programmes (Guries 1990). Provenance trials provide information about species' climatic adaptation that can be utilized for the prediction of the effects of environmental change (Matyas 1997; Rehfeldt *et al.* 1999).

The analysis of differences in seed-source performance and the corresponding differences in climate conditions at provenance origin allows for the interpretation of species or population responses across an environmental gradient (Thomson *et al.* 2009). Population response functions are models that are used to predict the effects of environmental or climatic changes on the future performance of a species or population. It is typically assumed that local seed source populations are broadly adapted to their local climate (Morgenstern and Mullin 1990). However, recent studies have demonstrated that southern seed sources often outperform local seed sources in common garden trials (Lu *et al.* 2016)

METHODS

STUDY SITE AND DATA COLLECTION

The Black Spruce Portfolio Test Compartment 17, located at the Natural Resource Centre (NRC) located at 25th Side Road (Lat. 48.37, Long. -89.39, Elevation. 300 m) (Figure 1), is an established research site focused on the transplantation of sixteen black spruce seed sources from Ontario, Quebec, Michigan, Wisconsin, and Minnesota. The trial was established to evaluate the performance of a mix of black spruce seed sources that were selected to perform well across a variety of future climate change scenarios (Nsiah 2014).

The present study applied the focal point seed zone method and a simplified version of the portfolio modelling approach to select 16 black spruce seed sources (Table 1) that may be suitable for reforestation under future climate uncertainty for the selected site in Northwestern Ontario. The test site was established in 2014 with 16 black spruce seed sources likely suited for future climates for the region. The test is arranged in a randomized complete block design. Within each block, 12 trees per provenance were arranged in plots of 3 x 4 trees with each plot being marked with an aluminum pole at each corner tagged with the seed source numbers (Appendix 1). A spacing of 1m x 1m was used as a planting distance for the test trees. Two border rows were established as a buffer surrounding the entirety of the test. The border was established to create a more uniform growing environment for the trees and to minimize edge effects. In total, 1920 trees were planted within the trial, with 432 trees planted as border trees for a total of 2352 trees.

The collection of field data for this thesis occurred throughout the week of October 11th to October 18th, 2022. I measured the height (Ht) of all surviving trees to the nearest centimetre using a fibreglass height measuring pole. The health of the tree was defined as healthy, broken-top, or dead. Trees with broken tops were categorized as dead trees for survival measurements and not included for height or productivity index calculations. Data was inputted manually utilizing mobile Microsoft Excel.

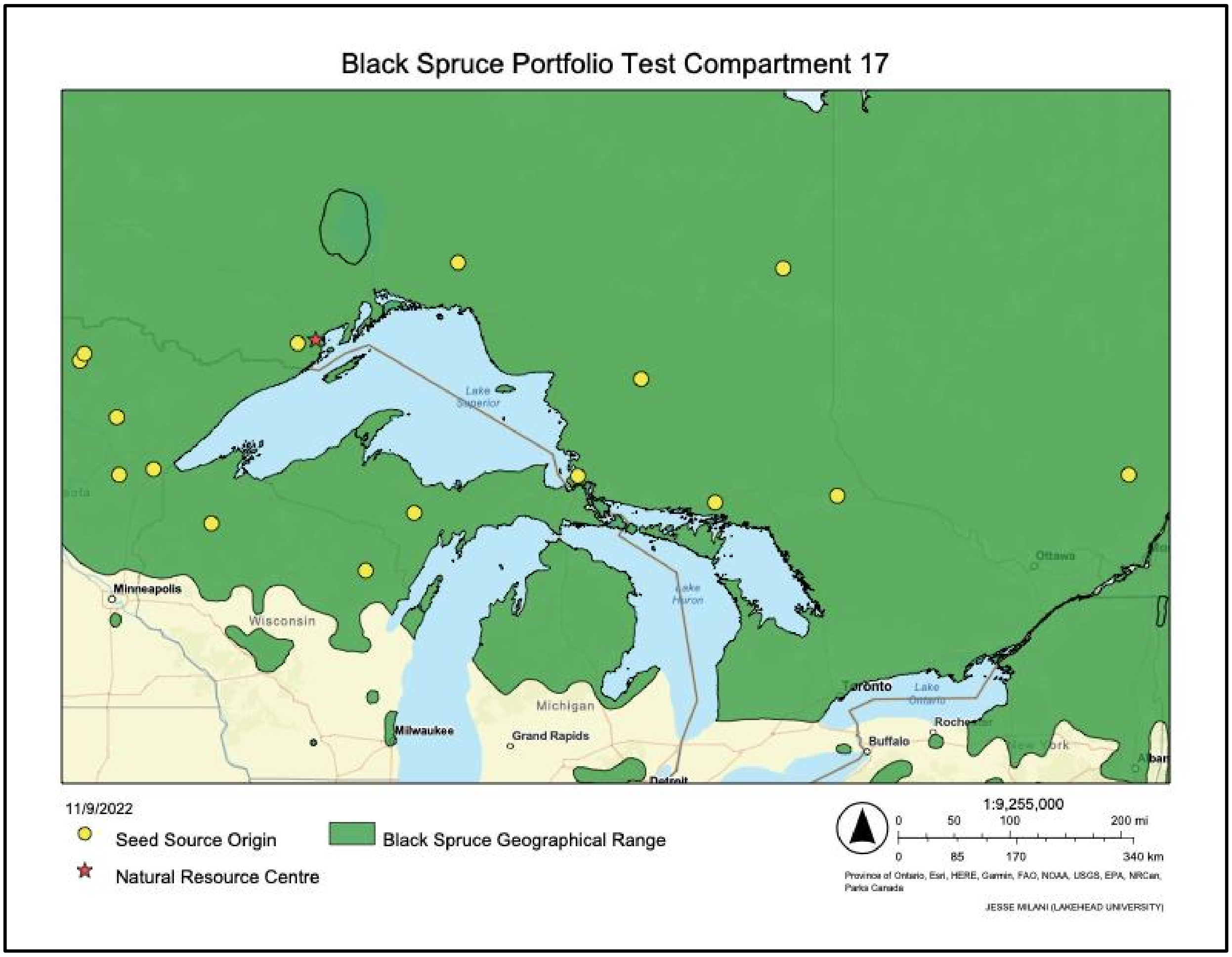

Figure 1: Geographic origin of black spruce seed sources and the test location.

Table 1: Geographic parameters of black spruce seed sources.

Agency	Seed Source Origin	Geographic Origin	Latitude	Longitude	Elevation (m)
CFS	1	St Michel des Saints, QC	46.63	-73.88	447
CFS	2	North Bay area	46.35	-79.45	318
CFS	3	Espanola area	46.27	-81.77	184
CFS	4	Cochrane Uplands 2	49.27	-80.47	314
CFS	5	Chapleau Highlands	47.87	-83.17	423
Clergue	6	Algoma Forest	46.62	-84.38	377
Green Forest	7	Aster Lake	49.33	-86.66	387
USFS	8	Upper Peninsula, Michigan	46.13	-87.50	330
USFS	9	Northeast Wisconsin	45.37	-88.43	376
Greenmantle*	10	Lakehead Forest	48.32	-89.72	300
USFS	12	Northwest Wisconsin	45.98	-91.37	426
USFS	13	Northeast Minnesota	48.10	-93.87	386
MN DNR	14	Cloquet, Minnesota	46.70	-92.47	363
MN DNR	16	Tamarack, Minnesota	46.63	-93.12	382
MN DNR	17	Nashwauk, Minnesota	47.38	-93.17	432
MN DNR	18	Big Falls, Minnesota	48.18	-93.80	373

* Local Seed Source

STATISTICAL ANALYSIS

The height and survival data were analyzed using IBM's Statistical Package for the Social Sciences (SPSS) software. I calculated the means and standard deviations of height and survival, excluding trees with broken tops. To test for statistical differences in height among seed sources, an analysis of variance (ANOVA) was performed on the height data using the General Linear Model (univariate) procedure of SPSS Software. Seed source and block were treated as random factors, and height was treated as the dependent variable. The average survival of each seed source was calculated by determining the number of surviving tree samples compared to the initial 120 trees planted. The Productivity Index of each seed source was calculated by calculating the average height of each provenance per block and multiplying it by the average survival (Saenz-Romero *et al*. 2021). The mathematical formula for PI is expressed as:

$$Productivity\ Index = average\ height * survivorship$$

CLIMATE DATA

The program ClimateNA v7.30 (Wang *et al*. 2016) was used to obtain regional climatic data for each seed source origin and the test site with a 4 x 4 km spatial resolution. Historical conditions were employed for each seed source location and test site utilizing the normal climate annual values for 1961-1990. The period was selected as it precedes recent increases associated with climate change negating adaptational lag in addition to coinciding with the peak weather station coverage in Canada (Pedlar *et al*. 2021). The variables utilized were the 1961-1990 Mean Annual Temperature (MAT, °C), Mean Summer Precipitation (MSP – May to September precipitation, mm), and Frost-Free Period (FFP, days) (Table 2). These variables were selected because they have been shown to be strong predictors of growth in other boreal studies (Rehfeldt *et al*. 1999; Wang *et al*. 2006; Rossi 2015; Thomson *et al*. 2009; Pedlar *et al*. 2021).

Table 2: Climate variables with ClimateNA Normal 1961-1990 mean annual temperature (°C) and mean summer precipitation (mm) for each seed source.

Seed Source	Latitude	Longitude	Mean Annual Temperature (°C)	Mean Summer Precipitation (mm)	Frost-Free Period (Days)
1	46.63	-73.88	2.4	512	110
2	46.35	-79.45	3.9	452	126
3	46.27	-81.77	4.2	381	125
4	49.27	-80.47	0.0	447	96
5	47.87	-83.17	1.4	407	103
6	46.62	-84.38	3.6	424	118
7	49.33	-86.66	-0.1	435	95
8	46.13	-87.50	5.0	450	120
9	45.37	-88.43	5.2	468	122
10*	48.32	-89.72	2.2	426	107
12	45.98	-91.37	4.6	519	120
13	48.10	-93.87	3.1	441	115
14	46.70	-92.47	3.8	473	113
16	46.63	-93.12	3.9	458	117
17	47.38	-93.17	3.3	467	117
18	48.18	-93.80	3.0	443	114
Mean			3.1	450	114

* Local Seed Source

RESULTS

SEED SOURCE PERFORMANCE

Mean heights for each provenance at 8 years ranged from the lowest value of 198.3 cm for seed source 4 to the highest value of 245.9 cm for seed source 8, with a mean height across all seed sources of 223.2 cm (Table 3). The calculated productivity index for each provenance ranged from the lowest value of 151.6 cm for seed source 8 to the highest value of 215.5 cm for seed source 6, with a mean productivity index value across all seed sources of 182.9 cm. Average survival ranged from a minimum of 62% for seed source 8 to a maximum of 94% for seed source 6, with average survival across all seed sources of 82% at 8 years. The standard deviation for average height averaged

8.1 cm and ranged from 0.8 cm for seed source 10 and 17.6 cm for seed source 4. The standard deviation for the productivity index averaged 10.4 cm and ranged from 1.1 for seed source 10 and 23.1 cm for seed source 6. The difference of height for productivity index to average height averaged -40.7 cm and ranged from -13.3 cm for seed source 6 to -94.3 cm for seed source 8.

Table 3: Comparative data results of 2022 average height, standard deviation, and average survival with calculated productive index from most productive to least productive.

Seed Source	Latitude	Longitude	Average Height (Ht) (cm)	Average Survival (%)	Productivity Index (PI) (cm)	Difference between PI and Ht (cm)	Standard Deviation (Ht) (cm)	Standard Deviation (PI) (cm)
6	46.62	-84.37	228.8	94	215.5	-13.3	3.9	23.1
9	45.37	-88.43	237.4	88	207.8	-29.6	10.0	17.6
18	48.18	-93.80	236.8	87	205.2	-31.6	9.6	15.8
16	46.63	-93.12	237.5	82	193.9	-43.6	10.1	7.8
17	47.38	-93.17	227.7	85	193.6	-34.2	3.2	7.6
13	48.10	-93.87	224.9	86	193.0	-31.9	1.2	7.2
12	45.98	-91.37	228.3	83	188.3	-40.0	3.6	3.9
10*	48.32	-89.72	224.3	81	181.3	-43.0	0.8	1.1
1	46.63	-73.88	205.7	88	180.0	-25.7	12.4	2.0
14	46.70	-92.47	207.0	86	177.7	-29.3	11.5	3.7
2	46.35	-79.45	214.4	82	175.1	-39.3	6.2	5.5
7	49.33	-86.66	208.9	83	174.1	-34.8	10.1	6.2
3	46.27	-81.77	232.4	73	170.4	-62.0	6.5	8.8
4	49.27	-80.47	198.3	82	162.0	-36.3	17.6	14.8
5	47.87	-83.17	213.3	73	156.4	-56.9	7.0	18.7
8	46.13	-87.50	245.9	62	151.6	-94.3	16.0	22.1
Mean			223.2	82	182.9	-40.7	8.1	10.4

* Local Seed Source

A one-way analysis of variance for height, survival, and productivity index indicates that height and survival are considered statistically significant, and the null hypothesis should be rejected for both, while the productivity index is not statistically significant, thus the null hypothesis is true (Table 4).

Table 4: A one-way analysis of variance of height, survival, and productivity index by seed source.

Variable	Source of variation	Sum of Squares	df	Mean Square	F	Sig.
Height	Between Groups	28826.965	15	1921.798	2.835	0.001
	Within Groups	97599.591	144	677.775		
	Total	126426.556	159			
Survival	Between Groups	0.836	15	0.056	2.099	0.013
	Within Groups	3.824	144	0.027		
	Total	4.660	159			
PI	Between Groups	49948.742	15	3329.916	1,538	0.099
	Within Groups	311766.566	144	2165.046		
	Total	361715.308	159			

A two-way analysis of variance for provenance and block effects indicates that each source is statistically significant, and the null hypothesis is rejected for each.

Table 5: A two-way analysis of variance for provenance and block effects.

Source	df	Type III SS	Mean Square	F Value	Pr > F
Block	9	204113.112	22679.234	9.08	<.0001
Prov	15	258764.205	17250.947	6.91	<.0001
Prov*blk	135	703528.953	5211.326	2.09	<.0001

REGRESSIONS OF GROWTH RESPONSES ON CLIMATE VARIABLES

For the climate variable mean annual temperature, a polynomial regression was completed with an R^2 value of 0.1819 while an R^2 value of 0.1102 was achieved through a linear regression (Figure 2). For the climate variable mean summer precipitation, a polynomial regression was completed with an R^2 value of 0.069 while an R^2 value of 0.0407 was achieved through a linear regression (Figure 3). For the climate variable frost-free period, a polynomial regression was completed with an R^2 value of 0.2277 while an R^2 value of 0.1191 was achieved through a linear regression (Figure 4).

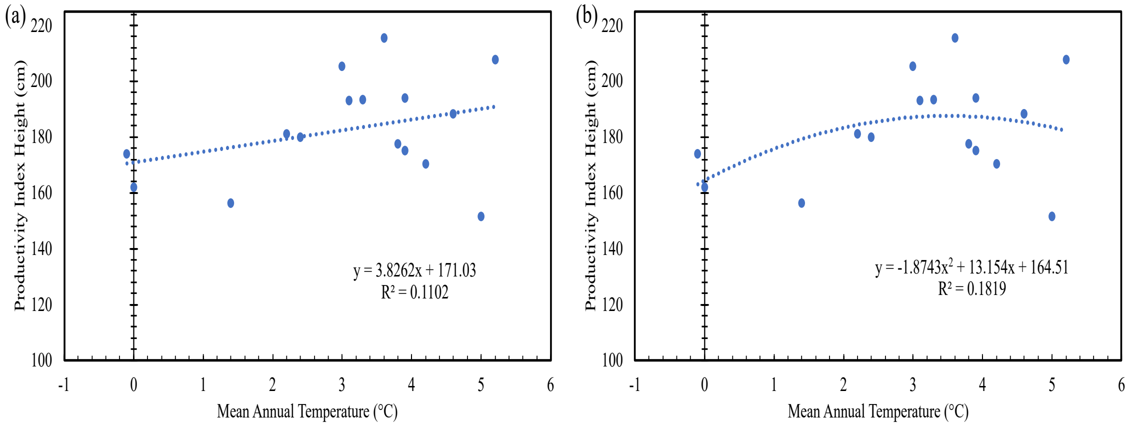

Figure 2: (a) Linear trendline for productivity index height (cm) over mean annual temperature (°C), (b) polynomial trendline for productivity index height (cm) over mean annual temperature (°C).

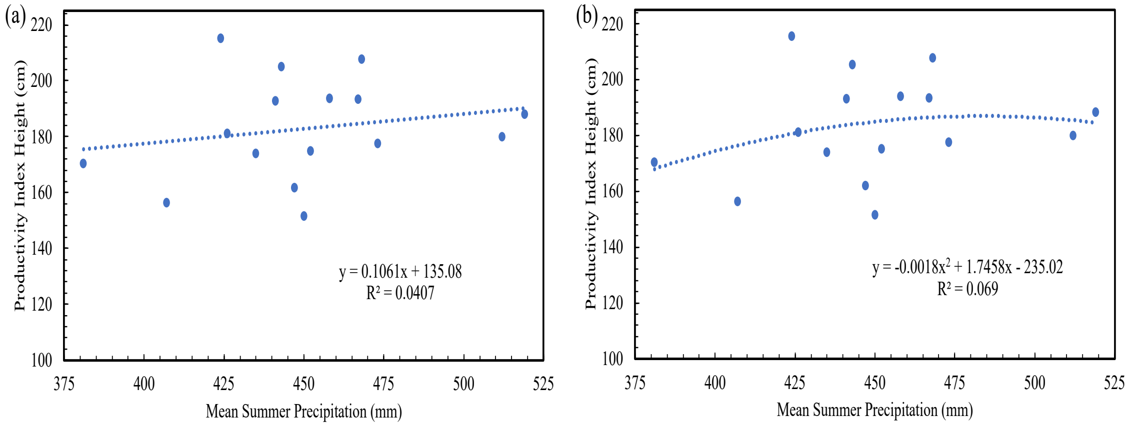

Figure 3: (a) Linear trendline for productivity index height (cm) over mean summer precipitation (mm), and (b) polynomial trendline for productivity index height (cm) over mean summer precipitation (mm).

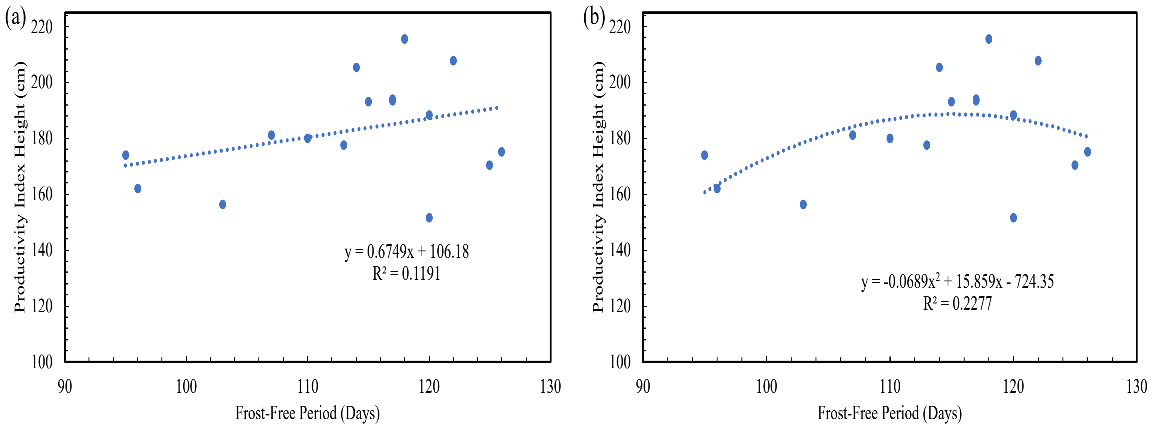

Figure 4: (a) Linear trendline for productivity index height (cm) over the frost-free period (days), and (b) polynomial trendline for productivity index height (cm) over the frost-free period (days).

DISCUSSION

This study found significant differentiation in height, survival, and productivity index among the black spruce seed sources. The regressions against mean annual temperature and frost-free period indicate that the existing variation is strongly associated with the climate at seed origin. This result is in agreement with previous studies of black spruce that report significant adaptive variation in relation to climate (Morgenstern 1986; Park and Fowler 1987; Thomson *et al*. 2009) and is in agreement with studies of other boreal conifers that report large amounts of adaptive genetic variation (Li *et al*. 2020; Pedlar *et al*. 2021; Lesser and Parker 2004) In my study, Ontario-based seed sources did not demonstrate the best survival and height growth. Seed sources 2, 3, 4, 5, 6, 7, and 10 all originated from Ontario, with only seed source 6 performing above the average for all attributes. Seed source 10, which originated from the local Lakehead Forest, performed below average for productivity index and survival. This result does not support the fundamental assumption that the use of local seed sources in reforestation programmes will always result in a reduced risk of maladaptation (Rehfeldt 1983; Lindgren and Ying 2000). However, this study does agree with the studies of (Parker 1992; Lesser and Parker 2006), which indicate that southern seed sources generally outperform their northerly counterparts when planted in a common garden. My study found seed sources from Northern Minnesota (seed sources 13, 16, 17, and 18) and Wisconsin (seed sources 9 and 12) performed better than average for both survival and productivity index compared to local seed sources. The most successful seed source was seed source 6 from the Algoma forest. Through the success of southwestern seed sources and the poor success of local seed sources, this highlights the potential for assisted migration to improve growth and productivity under climate change (Thomson *et al*. 2009; Pedlar et al. 2021; Morgenstern and Mullin 1989).

Seed sources exhibited a polynomial relationship between height growth and the climate variables MAT, MSP, and FFP (Figures 2, 3, and 4) which was stronger when compared to the linear regressions. A polynomial relationship indicates a heightened complexity of the relationship of response variables with climate that a linear regression does not describe well. The climate variable frost-free period was a stronger indicator for the productivity index when compared to the mean annual temperature and mean summer precipitation based on a polynomial relationship. Other provenance studies have found temperature variables to be strong predictors of tree growth and survival, whereas precipitation variables are generally poor predictors (Pedlar *et al*. 2021; Thomson *et al*. 2009; Rossi 2009). Based on a study conducted by Hofgaard *et al*. (1999), precipitation was a relatively weaker predictor of growth than temperature for black spruce in Quebec. Viereck and Johnston (1990) suspect that precipitation is a poor indicator of black spruce height growth due to the fact the species can occupy upland and lowland sites with a variety of moisture conditions. Morgenstern and Mullin (1989) found that the frost-free period was one of the strongest predictors of height and survival in their study of black spruce provenance tests in eastern Canada. Li *et al*. (2020) conducted a similar provenance trial on red spruce (*Picea rubens*) and concluded that the frost-free period and mean annual temperature had the most significant impact on tree height.

Considering only height, multiple seed sources appeared to be the best suited for transplantation at the Thunder Bay site. Specifically seed source 8 from Michigan and seed source 3 from Espanola. Both seed sources had a higher mean height when compared to the mean across all 16 seed sources, with an average height of 245.9 cm for seed source 8 and 232.4 cm for seed source 3 compared to the mean of 223.2 cm. However, these two seed sources had the lowest survival percentage with 62% of seed source 8 and 73% of seed source 3 surviving since planting. Both seed sources had a positive deviation value in relation to the average height mean with a value of 16.0 cm for seed source 8 and 6.5 for seed source 3 cm before calculating PI. The calculated productivity index suggested that these sources are not the best performers under current climate conditions, as their PI was below the mean of the 16 seed sources. Seed source 8 calculated PI value was 151.63 cm and seed source 3 had a PI value of 170.43 compared to the mean of 182.9 cm. With calculated PI, both seed sources had a negative deviation value in relation to the PI mean (182.87 cm) with a value of 22.1 cm for seed source 8 and 8.8 cm for seed source 3. The difference between the average height and the PI for seed sources was 62.0 cm for seed source 3 and 94.3 cm for seed source 8. Without a calculated productivity index and incorporation of survival percentage, these two seed sources would likely be determined to be best suited for transplantation and growth for future management approaches. Thus, this study highlights the importance of considering both growth and survival variables in identifying suitable seed sources for reforestation under climate change.

FUTURE IMPLICATIONS

Maladaptation to climate reduces tree productivity, results in poor stem form and wood quality, and increases susceptibility to pests and disease (Johnston *et al*. 2009). Significant maladaptation is expected to occur in Canadian tree species due to the unsynchronized growth cycle of trees in relation to the annual climate cycles to which trees are genetically adapted. Therefore, the establishment of plantations with populations adapted to future climates has been posed as a key climate change adaptation strategy (Rehfeldt *et al*. 2006; Miller *et al*. 2007). The proactive intervention through assisted migration of seed during the establishment of plantations is likely to help maintain the optimum health and productivity of Canadian forests (Rehfeldt *et al.* 1999; Wang *et al*. 2006). The black spruce portfolio trials established at the Natural Resource Centre will continue to assist as a long-term study testing black spruce responses to climate change, in addition to the optimizing of decision-making tools for planned adaptations to future climate change uncertainty. My study identified several seed sources (Algoma Forest, Northeast Wisconsin, and Northern Minnesota) that demonstrate relatively high survival and height growth and thus are ideal candidates for future reforestation in the Thunder Bay area. These seed sources performed best in climate conditions experienced over the past eight years but may not be the best performers for distant future climate periods (i.e. 2041-2070, 2071-2100). However, it should be reasonable to expect these sources to continue performing well over the next 10 to 20 years. Seed sources from the Upper Peninsula Michigan, Chapleau Highlands, and Cochrane Uplands performed the poorest in the trial. Current Ontario climate-based seed transfer policies are now mandatory for forest managers to consider when making seed transfer decisions (MNRF, 2020). Seed transfer direction based on demonstrated patterns of adaptive variation is currently being developed for major species in Ontario. Such guidelines would benefit from information on variation in additional traits compared to those measured in the study. For example, further research at the Thunder Bay assisted migration trial could focus on phenological traits, such as timing of flowering or bud burst, which are expected to be highly sensitive to climate change (Rossi 2015). Furthermore, within the study, a high percentage of tree mortality occurred from an unknown cause in which the terminal stem became weakened and broken. An additional investigation should be performed to identify potential indicators.

CONCLUSION

This study supports the hypothesis that reforestation using black spruce seed sources from southern latitudes would result in superior height growth performance and survival compared to reforestation with seed sources local to the Thunder Bay area. The seed source from the Algoma forest had the highest level of survival and productivity index, making it the most suitable source for seed transfer measures under current climate conditions. The local seed source performed below average for both survival and productivity index, further supporting the hypothesis that local seed sources are not necessarily the best seed source in a changing climate. Additionally, five of the other six Ontario seed sources ranked below average on both parameters. The one seed source from Quebec performed below both the average survival and productivity index parameters. Seed sources from Wisconsin and Minnesota performed well in the study, while one seed source from Michigan had the poorest performance of the 16 seed sources. This study indicates that assisted migration seed transfer approaches should use height growth as a primary indicator and survival and productivity index as main responses. The Black Spruce provenance trial at the Natural Resource Centre will continue to serve as a trial for understanding assisted migration measures in a changing climate.

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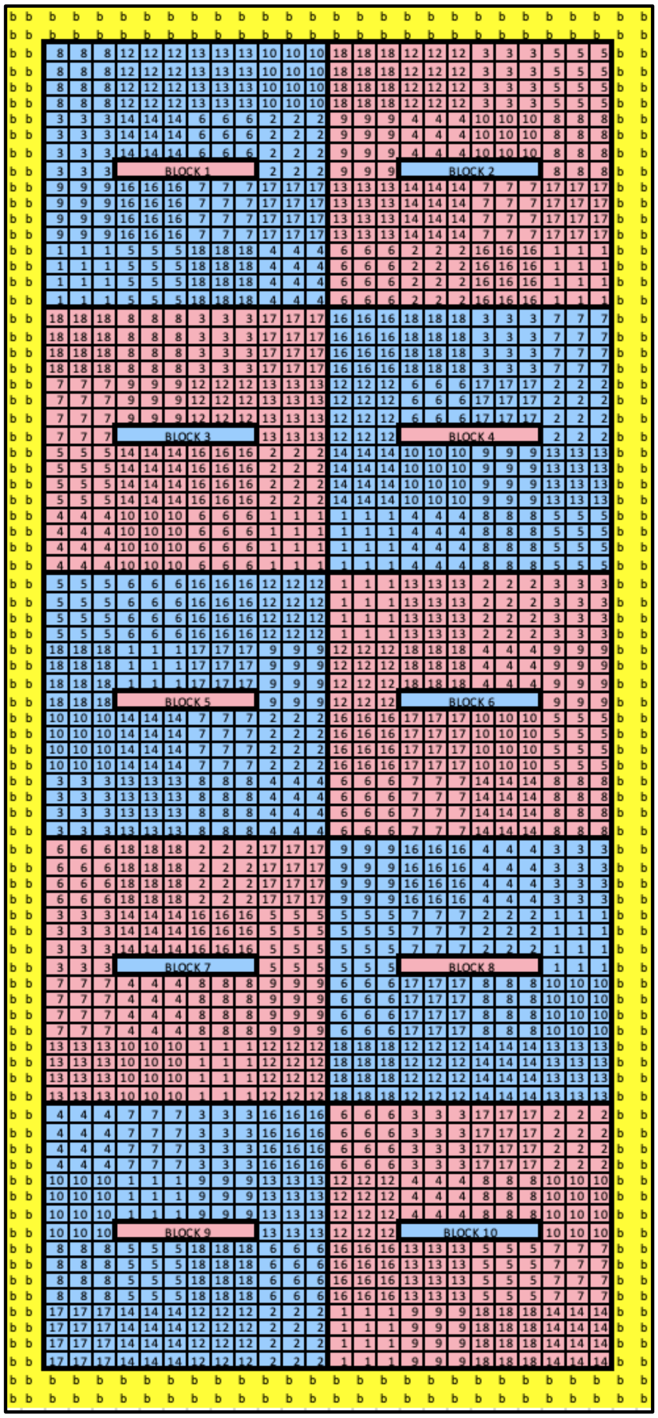
APPENDIX

APPENDIX 1: 25TH SIDE ROAD TEST DESIGN.



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b	b	18	18	18	1	1	1	17	17	17	9	9	9	12	12	12	18	18	18	4	4	4	9	9	9	b	b
b	b	18	18	18	BLOCK 5						9	9	9	12	12	12	BLOCK 6						9	9	9	b	b
b	b	10	10	10	14	14	14	7	7	7	2	2	2	16	16	16	17	17	17	10	10	10	5	5	5	b	b
b	b	10	10	10	14	14	14	7	7	7	2	2	2	16	16	16	17	17	17	10	10	10	5	5	5	b	b
b	b	10	10	10	14	14	14	7	7	7	2	2	2	16	16	16	17	17	17	10	10	10	5	5	5	b	b
b	b	10	10	10	14	14	14	7	7	7	2	2	2	16	16	16	17	17	17	10	10	10	5	5	5	b	b
b	b	3	3	3	13	13	13	8	8	8	4	4	4	6	6	6	7	7	7	14	14	14	8	8	8	b	b
b	b	3	3	3	13	13	13	8	8	8	4	4	4	6	6	6	7	7	7	14	14	14	8	8	8	b	b
b	b	3	3	3	13	13	13	8	8	8	4	4	4	6	6	6	7	7	7	14	14	14	8	8	8	b	b
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b	b	3	3	3	14	14	14	16	16	16	5	5	5	5	5	5	7	7	7	2	2	2	1	1	1	b	b
b	b	3	3	3	BLOCK 7						5	5	5	5	5	5	BLOCK 8						1	1	1	b	b
b	b	7	7	7	4	4	4	8	8	8	9	9	9	6	6	6	17	17	17	8	8	8	10	10	10	b	b
b	b	7	7	7	4	4	4	8	8	8	9	9	9	6	6	6	17	17	17	8	8	8	10	10	10	b	b
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b	b	10	10	10	BLOCK 9						13	13	13	12	12	12	BLOCK 10						10	10	10	b	b
b	b	8	8	8	5	5	5	18	18	18	6	6	6	16	16	16	13	13	13	5	5	5	7	7	7	b	b
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