EARLY GROWTH RESPONSES OF BLACK SPRUCE SEED SOURCES
SELECTED FOR REFORESTATION UNDER CLIMATE CHANGE SCENARIOS IN
ONTARIO

By

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ABSTRACT

Reforestation programmes under changing climates requires an understanding of species adaptive patterns of variation. Such information is vital in identifying and matching uniquely adapted seed sources to areas of optimum growth, conserving the genetic variation of the species as well as reducing the risk of using maladapted sources. This study examined early growth responses of selected black spruce (*Picea mariana* (Mill.) B.S.P) seed sources identified for reforestation through the application of a portfolio theory model and planted at three climatically diverse sites in Ontario. Two sequential modeling approaches were applied; 1) the species range impact model which uses biological growth responses and climatic data to determine how well a seed source will grow at a given site under different climate change scenarios, and 2) the portfolio model which selects a set of seed sources that collectively reduce risk of maladaptation. Significant variations were found in the growth responses of black spruce seed sources growing at the three sites. Seed sources originating from the southerly portions of the test locations demonstrated superior growth. Principal components analysis of fall height, spring height, increment and survival showed that a high proportion of the variation among the seed sources can be explained by fall height growth. Among climate variables, minimum and maximum temperatures and precipitation in the spring, summer and fall growing seasons were identified as good predictors of black spruce growth. The results suggest that black spruce seed sources are adapted to their local climates and that future climate can result in maladaptation of the species within their current ranges. The capability of the applied models to identify well adapted seed sources and match the sources into required future climates is novel and invaluable. The results and model predictions have wide implications for biodiversity conservation efforts and may be

useful in seed transfer programmes under the changing climates. The early results suggest that the combination of species range impact model and portfolio decision support model identify an adaptive pattern of variation from multiple seed sources, and select a set of sources to succeed under a multiple climate change scenarios. Also, the result gives an indication that southern seed sources may well be suitable for future reforestation programmes in the Ontario Boreal Forest Region.

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INTRODUCTION

Climate is the primary force that determines species composition and vegetation type of an area; and as such, the effects of climate change, specifically changes in temperature and precipitation, pose challenges to forest management (Jenny 1941; Davis 1989; Rizzo and Wiken 1992; Iverson and Prasad 2001; Newton *et al.* 2007). With increasing climate change events, forest managers will continue to face the challenge of maintaining ecological functions of forests and the sustainable production of wood and timber. Climate will continue to change (Harrington 1987; Trenberth *et al.* 2007; IPCC 2007; IPCC 2013); however, depending on emission scenarios and climate feedbacks, there is no definitive prediction of the magnitude of change (Nakicenovic *et al.* 2000; Crowe and Parker 2008). For instance in North America, General Circulation Models (GCMs) have predicted average temperature increases between $2^{\circ}C$ to $5^{\circ}C$, with warming expected to be higher in the northern latitudes (IPCC 2007). In Canada, McKenney *et al.* (2009) predicted changes in annual temperature to be between $1.5^{\circ}C$ to $4.2^{\circ}C$ by 2040; $4.5^{\circ}C$ to $7.5^{\circ}C$ by 2070; and $7.0^{\circ}C$ to $10.3^{\circ}C$ by 2100. Precipitation is also expected to decrease or increase in some regions. Historical data showed increased precipitation in the north and south western regions of Canada over the period 1950 to 2005, and it is projected to increase 20% to 30% by 2100.

As climate change occurs, it is expected that plant growth and survival may be affected because current habitats where tree species grow may no longer provide adequate conditions for future growth (Papadopol 2000). In the boreal forest, for example, changes in the climate are related to frequent occurrences of forest fires, pest outbreaks and drought (Flannigan and Wagner 1991; Wotton *et al.* 2005; Lempriere *et al.* 2008;

Michaelian *et al.* 2011). Changes in tree phenology and species ranges have also been

attributed to the changing climate (Parmesan and Yohe 2003; Parmesan 2006). It may be

possible for tree species to survive and adapt in the changing climates because of their

phenotypic plasticity (Jackson *et al.* 1997; St Clair and Howe 2007; Crowe and Parker

2008; Wang and Morgenstern 2009); however, there is a limitation to adaptation, and

extinction is possible in instances of rapid climate change (Peters 1990; Davis and Shaw

2001; Nielson *et al.* 2005; Nielson *et al.* 2009). In addition, trees migration may be

restricted due to ecosystem fragmentation (Noss 2001; Fahrig 2002).

With recent shifts in regional climate, maladaptation of tree species is expected to

occur including most commercially traded wood species in boreal forests (Schmidtling

1994; Rehfeldt *et al.* 2006). In Canada, about 400,000 ha of forest land are regenerated

annually (McKenney *et al.* 2009), and black spruce is commonly used in reforestation

programmes because of high utilisation of its products (Ladell 1970; Margolis and Brand

1990; Wang *et al.* 1994).

The black spruce species is widely distributed across Canada's boreal forest,

extending from Newfoundland to Alaska (Hoise 1967). Black spruce is found in a variety

of habitats (Jeglum 1974) and regenerates naturally after fire disturbance or clearcutting.

Fleming (1990) identifies moisture deficits, and low soil and air temperatures as

constraints to black spruce regeneration. Although black spruce usually forms pure stands

on shallow and poorly drained soils, yield is generally higher on nutrient rich sites

(Hearnden 1975). Black spruce populations are generally adapted to their local

environment; however, as climates change, their responses to the climate differ

significantly (Morgenstern 1978). The concern of climate change impacting on black

spruce sustainability has resulted in several adaptation initiatives to conserve and increase

the species productivity in Ontario boreal forest region. For example, Van Damme and Parker (1987) used plus-tree selection for superior growing space efficiency. Thomson *et al.* (2009) developed transfer functions of height growth. Also, Parker (1992), Parker and Van Niejenhuis (1996) developed a site-specific focal point seed sources approach to match seed sources to areas of similar adaptive traits.

In many instances, several approaches have also been used as a planned adaptation strategy to climate change (IPCC 2007) including cost-benefit analysis, cost-effectiveness analysis and policy approach. However, Lempert *et al.* (2004) indicate that for planned adaptation to climate change the strategies that need to be employed must offer solutions that perform equally well against all considered climate scenarios.

Because of the long rotation periods of trees and the inability to make a definitive prediction of future climate, the use of seed sources adapted to equally plausible future climates is important for planned adaptation in reforestation (Crowe and Parker 2008; Ukrainetz *et al.* 2011). Selection of adaptive seed sources for reforestation may prove to be vital in conserving the genetic variation of tree species and may also minimise risks of tree maladaptation and increase productivity (Ledig and Kitzmiller 1992; Eriksson *et al.* 1993; Rehfeldt *et al.* 2006; St Clair and Howe 2007). The overall purpose of this study is to determine early growth responses of black spruce seed sources selected for reforestation through the applications of species range impact model and portfolio theory model and planted at three climatically diverse sites in Ontario. Specifically, the study is to conduct an early evaluation of black spruce seed sources predicted by portfolio theory to be potentially adaptable for reforestation at the selected sites in Northern and Central Ontario.

LITERATURE REVIEW

Climate uncertainty and planned adaptation

There are several conceptual definitions of climate change. For example; United Nations Framework Convention on Climate Change (UNFCCC) defines it as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which in addition to natural climate variability observed over comparable time periods (UNFCCC 2013). Intergovernmental Panel on Climate Change (IPCC 2001) also defines climate change as a statistically significant variation in the mean state of the climate or its variability, persisting for an extended period. Other studies (Hare and Francis 1995) conclude that climate change is the change in the average weather that a given area experiences over a long period of time. Ultimately, climate change is understood to be the likely result of natural processes and external forcing, as well as the continuous releases of anthropogenic gases into the atmosphere or land-use.

The climate drivers of particular concerns are the future concentrations of atmospheric CO_2, and the resulted changes in temperature and precipitation (Millennium Ecosystem Assessment 2005; Newton *et al.* 2007). Several predictions have been made from different geographic locations and depended on the emission scenarios and models (Prentice *et al.* 2001; IPCC 2007; Trenberth 2010), climate will continue to change. However, the scenarios and models for future climates estimates are subject to uncertainty (Klein *et al.* 2005). Compounding the uncertainty is recent use of advanced computer models for the climate estimates. The evaluation of many atmosphere-ocean general circulation models (AOGCMs) concluded that, although models are able to make

credible climate stimulations for large scales; to some extend all the models have inherent errors since the models differ in their outputs (IPCC 2007; Solomon 2007; Trenberth 2011).

Scenarios A1, B1, A2, and B2 have widely been used to make future climate estimates (IPCC's Special Report on Emission Scenarios 2001 and 2007). In the A1 scenario, future climate estimates depend on rapid economic growth, global population increases, and continual technological advancement. In contrast, the B1 scenario is based on cleaner resources and more efficient technologies, although there is doubt about whether the B1 scenario is realistic (Schneider 2001). In the A2 and B2 scenarios the projected rates of human population growth, deforestation, air pollution and CO_2 emission are considered to be three times higher than the current rates by the end of the century. However, irrespective of the emission scenario used, the atmospheric CO_2 emissions are projected to increase between 11.0 Gt C to 23.9 Gt C by 2050 (Prentice *et al.* 2001), way beyond the 1990s emissions estimates of 6.3 Gt C per year from fossil fuels with an additional 1.7 Gt C from land use change (Schimel *et al.* 2001).

Similarly, the global temperature is projected to increase between 1.1°C to 6.4°C by the year 2100 (Schneider and Lane 2006; IPCC 2007). Cubasch *et al.* (2001) predict an increase in mean global temperature over next 100 years between 1.4°C and 5.8°C with different emission scenarios. Other studies employing more and comprehensive feedbacks also estimate future temperature increase of up to 8°C by year 2100 (Andreae *et al.* 2005; Meinshausen *et al.* 2009).

In North America, temperature increase between 2°C to 5°C with warming more pronounced in the northern latitudes have been predicted (IPCC 2007), whereas

McKenney *et al.* (2009) study found minimum temperature increase of 5°C to10°C across the seed zones of British Columbia and Ontario provinces by 2100.

Global precipitation is not projected to be constant in all regions. Precipitation was found to have increased by 10% to 40% over the past 100 years in the northern Europe, but has decreased by 20% in the southern Europe (Newton *et al.* 2007). In Ontario, the historical data of precipitation were found to be high in the southern and northwestern regions of the province, and it is estimated to increase 20 to 30% by 2100, particularly in the Central part of the province (McKenney *et al.* 2009).

The inconsistency and degree of climate uncertainty is due to the probability and magnitude of atmospheric CO_2 that is predicted to occur under a given scenario (Read 2004). Since the estimates are based on the patterns of economic development, population growth, and technological advancement and other feedback processes that are not easy to predict over long periods (Parry 2007; Rivington *et al.* 2008; Smith *et al.* 2009; Park and Talbot 2012). Atmosphere-Ocean Global Circulation Models that have been used to simulate climate change include: the Canadian GCM (CGCM2, Boer et al. 2000a), the UK-based Hadley GCM (HADCM3, Gordon et al. 2000), the Australian-based Commonwealth Scientific and Industrial Research Organisation GCM (CSIROMk2, Gordon and O'Farrell 1997), and the American-based National Centre for Atmospheric Research GCM (NCAR, Collins et al. 2006).

Climate change and Boreal forest tree species

Evidence from paleoclimatic studies show the global, regional, and local climates are changing. Such forecasts are supported by studies from rocks, sediments, ice sheets, tree rings, corals and microfossils (Thomas *et al.* 2004; Lovejoy 2006; IPCC 2013); although the fossil records are not as fine as the records from 1850s when direct measurement of temperature began. In any case, the global temperature and precipitation changes have empirical effects on the boreal forest.

In Canada, the impacts of the changing climate on forests are generally related to frequent occurrences of wildfires (Flannigan and Wagner 1991; Stocks *et al.* 1998), pest outbreaks and drought (Kurz *et al.* 2008; Lempriere *et al.* 2008; Michaelian *et al.* 2011), large-scale shifting of forest vegetation (Rizzo and Wilken 1992; Smith and Shugart 1993), species maladaptation (Schmidtling 1994; Rehfeldt *et al.* 2006). Effective 2004, about 1.7 million hectares of forest were burned in Yukon, and over 300,000m^3 of timber was removed through salvage felling due to spruce bark beetle (*Dendroctonus rufipennis*) infestation. A study on these disturbances indicated an association to climate change impacts (Ogden and Innes 2008).

Kremer *et al.* (2007) observed that evolutionary mechanisms contributing to species adaptation to climate change is acting at an individual, population and species levels. Studies on trees phenology and physiological changes have been observed under the changing climates, and the conclusion is that climate change is already affecting living systems (Parmesan and Yohe 2003; Parmesan 2006). For example acclimation was found to be a gradual response to increasing CO_2 concentration. Tjoelker *et al.* (1999) and Bolstad *et al.* (2003) found that some trees increase their respiration when exposed to high temperatures and then partially adjust when temperature was reduced. This

phenomenon was observed for jack pine (*Pinus banksiana* Lamb), white birch (*Betula papyrifera* Marshall), and black spruce seedlings. Muller-Starck (1989) isozyme study showed heterozygosity in individual tolerant beech trees was greater than the heterozysity of sensitive beech trees particularly in more polluted altitudes. Although, interpretation of heterozysity is controversial, some authors believe increased heterozysity is a mechanistic approach to eliminate inbred genotypes (Ledig 1986), whereas others believe it contributes to individual fitness towards extreme environmental changes (Mitton and Grant 1984; Mitton 2000). Similarly, Torti's (2005) investigation in quantitative trait loci (QTL) detection found that the number and contributions of QTLs vary according to CO_2 concentration. Until then the gradual decrease of birch leaf stomatal density (Wagner *et al.* 1997) was considered to be the plant physiological adaptation to the environmental change. In many instances (Nicotra *et al.* 2010) observed that temporal changes in the local climates, for example, year after year changes result in distinct responses in local genotypes such as flowering.

Many tree species are genetically adapted to their local environment (Woodward 1987), and as such species ranges are expected to change as the climate changes rapidly. Differentiation in tree populations throughout species ranges have been attributed to natural selection (Morgenstern 1978; Pollard and Logan 1974; Konig 2005). Crowe and Parker (2008) also showed black spruce seed sources respond differently with respect to particular climate scenarios. In addition, maladaptation is predicted to be possible if current climate change exceeds the rate trees can migrate to new areas (Schmidtling 1994; Rehfeldt *et al.* 2006).

To maintain forest health and productivity redistribution of tree species across the wider landscape or using adaptable seed sources in seed transfer programmes have been suggested to be useful (Ukrainetz *et al*, 2011; Rehfeldt *et al.* 1999).

Planned adaptation in response to climate uncertainty

Ecological niche approaches for predicting plants under future climate scenarios show that species' ranges may shift from tens to hundreds kilometers over the next 50 to 100 years, much faster than what has occurred in the last glacial period (Davis and Zabinski 1999; Malcom *et al.* 2001; Davis *et al.* 2005; Thomas *et al.* 2004; Iverson *et al.* 2008), and that species that could not migrate at the rate of climate change might lose their ability to function or become extinct. Thus, the geographic range and habitats in which species grow and survive may reduce their adaptive capacity to respond to climate change (Neilson *et al*, 2005; Skelly *et al.* 2007). Although, some studies (Jackson *et al.* 1997; Thuiller *et al.* 2006; Kremer *et al.* 2007; Wang and Morgenstern 2009) consider that many trees have potential to migrate and adapt to the changing climate because of their high genetic variation and phenotypic plasticity, others show adaptation was limited when climate change occurred more rapidly (Davis and Shaw 2001; Aitken *et al.* 2008). This mixed situation is because the immobility of trees coupled with their long rotation periods makes them less adaptable to faster rates of climate change (Peters 1990; Vitt *et al.* 2010).

The uncertainty associated with climate change and the ecosystem fragmentation requires planned adaptation that will prevent species extinction and extirpation, minimize economic loss and sustain ecosystem multiple functions and biodiversity (Millennium Ecosystem Assessment 2005). Adaptation is defined as adjustment that occurs in natural

or human systems in response to actual or expected impacts of climate change, aimed at moderating harm or exploiting beneficial opportunities (Klein *et al.* 2005). Planned adaptation is undertaken to effectively manage potential risk associated with climate change. Decision for adaptation could be a short-term or long-term, and under spatial, temporal or sectorial scale (Howden *et al.* 2007). For example, local scale adaptation may be useful in the short-term if there is correlation between local climate trends and projected climate changes. However, in the long-term there will be limitation in their adaptation due to the high uncertainties at the finer scale climate projections. In contrast, long-term adaptation will be useful due to reliable climate projection at larger time and spatial scales. A significant benefit for an adaptation strategy may be how short-term strategies link to long-term options to ensure that an adaptation strategy can be effective over plausible climate change events.

Many decision frameworks have been developed to guide adaptation to climate change (Ohlson *et al.* 2005; Tschakert and Olsson 2005). IPCC's Third Assessment Report (IPCC 2007) identifies some of the major frameworks applied in climate adaptation. These frameworks include: cost-benefit analysis, cost-effectiveness analysis, and the policy-exercise approach. In forestry, management practices such as changes in; i) forest management intensity, ii) harvesting patterns within and between regions, iii) rotation periods, iv) salvaging dead timber, and v) planting different species that can be productive under the new climatic conditions. Also landscape planning to minimize fire and insect damage has been identified as a climate adaptation strategy (Howden *et al.* 2007). Crowe and Parker (2008) used modern portfolio theory to reduce risk and maximize returns in reforestation programme under future climate uncertainty. The modern portfolio theory provides risk-return analysis under the environment of

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uncertainty. Similarly, movement of seed sources and populations of trees within their current range (assisted population migration), or from their current range to suitable areas just outside their range (assisted range expansion), or to locations far outside their current (assisted species migration) have been suggested as an adaptation strategy in reforestation programmes (Aubin *et al.* 2011; Winder *et al.* 2011; Williams and Dumroese 2013). Such management practices are currently underway for the tree species Florida torreya (*Torreya taxifolia Arn.*) in the United States (Gray and Hamann 2013; Torreya Guardians 2012).

Ultimately, climate adaptation programmes require integrated approaches to become more dynamic, to cope with the high level of uncertainty in the timing and magnitude of potential climate changes and the evolving knowledge.

Black spruce ecology and silvics

Black spruce is one of the most commercially important tree species in Canada. The species is widely distributed across the boreal forest in Ontario and the rest of Canada, extending from Newfoundland to Alaska (Hoise 1967). Black spruce is found in a variety of habitats (Jeglum 1974) and regenerates naturally after disturbance such as fire or by clearcutting; artificial regeneration is also possible through planting. The species usually grows on wet organic soils, but productive stands are found on a variety of soil types; deep humus, clays, loams, sands, coarse till, boulder pavements, and shallow soil mantles over bedrock (Viereck and Johnston 1990). Selection of site for regeneration is not only limited to biological factors, but considerable non-biological factors such as economics or methods for site preparation. Site preparation enhances the tree performance which includes high seed germination and seedlings survival.

Fleming (1990) identifies several constraints to black spruce regeneration. Such constraints include near-surface and root zone moisture deficits, and low surface and soil subsurface temperatures. Other stresses also include extreme light, nutrients, soils and or atmospheric chemistry (Levitt 1980). Although black spruce usually forms pure stands on shallow, poorly drained, and cold soils, yield increment per hectare is dependent on site quality (Hearnden 1975; Morgenstern 1978).

Like many boreal forest conifer species, black spruce provenances, seed sources and populations exhibit large amount of genetic variation which is adaptive, and that the species adaptive characteristics are clinal, primarily along a north-south geographical gradient (Khalil 1975). Differentiation in photoperiod response, productivity, germination, cone and seed yield, height and survival rate has been shown to be related to the geographical area of seed origin (Morgenstern 1973). Introgressive hybridization between black spruce and red spruce has been reported in Nova Scotia, New Brunswick, and Quebec (Morgenstern and Farrar 1964; Gordon 1976).

Commercially, black spruce is used extensively both in Canada and the United States for making high quality pulp with balanced strength properties. The species is also used for lumber, Christmas trees, and other products. Historically, black spruce exuded resin has been used as a healing salves, beverages from twigs and needles, aromatic distillations from needles, and binding material for canoes (Safford 1974). Many bird species also depend on black spruce stands as habitat, or feed on the seeds.

METHODS

Philosophical Background

The background of the study was based on functional application of two useful modeling approaches: (1) the focal point seed zone method/the species-range impact model (Parker 1992, Parker and Van Niejenhuis 1996; Lesser and Parker 2004; Ukrainetz *et al.* 2011); and (2) the portfolio decision support model (Crowe and Parker 2008; Crowe and Parker 2011; Weng *et al.* 2013). The focal point seed zone method is a unique approach for matching a set of seed sources to a specific location based on the adaptive variation of the seed sources. This approach is proved to be vital for planned adaptation for genetically variable tree species. The method is based on the availability of two sources of data: (a) growth responses of multiple seed sources grown under different climate environment established in a common garden trial; and (b) high resolution climatic data for the seed sources origin. The output from focal point seed zone model is then used in the portfolio model.

Five principal procedures are involved in the species-range impact model. First, biological growth responses of the seed sources are determined from common garden trials, and a statistical approach is used to estimate differences in the growth responses. Second, high resolution climate grids based on Global Circulations Models (GCMs) are used to determine whether the biological variation determined in growth responses among different seed sources grown in different geographic locations is influenced by climate variables. High resolution climate grid is preferential to using recorded climate values from the nearest meteorological stations in species-range impact model because it estimates climatic differences between seed sources within adjacent geographic locations

(McKenney 2007). Third, principal component analysis (PCA) is used to summarize the growth responses variables into principal component axes. Fourth, standardized PCA axes scores are then used in multiple regressions against the climate variables of the seed sources locations to generate trend surfaces for each PCA axis representing adaptive variation of the seed sources. Finally, to produce focal point seed zone of any location, two or three contour maps, corresponding to the main axes of variation and standardized to the focal point values are overlaid with the interval set to a desired limit.

The focal point seed zone represents a potentially unique procurement area for any specific seed source. Based on available empirical data, the species-range impact modeling approach is capable of predicting variation that is adaptive in nature among multiple seed sources and matching the seed sources to areas with similar adaptive traits. The usefulness of this model over other conventional species distribution models is that it makes it possible to estimate how well a species, adapted to its current/present day climate, will perform when moved into a different geographic location under a specified future climate scenario. The output from the focal point seed zones model is used to generate the portfolio decision support model. The original preposition of the portfolio optimization model is to consider the desirability of assets diversification under uncertainties. Crowe and Parker (2008) applied portfolio theory for selecting multiple seed sources of white spruce for reforestation under future climate uncertainties. Their study showed that the seed sources are not selected to perform equally well across all plausible futures but rather the sources are selected to specialise in equally probable climate change scenarios. Weng *et al.* (2013) also demonstrated the application of portfolio theory to improve yield and reduce risk in black spruce family reforestation. Their results indicated that portfolio theory model searches for the combination of yield

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and stability and produces family portfolios that maximize yield at a given stability or

minimizes yield instability at a given yield, and that portfolio model is useful to improve

yield over the conventional truncation-deployment family forestry method. Specifically,

the principle of portfolio theory model is to select a set of seed sources for reforestation

that collectively reduces risk of maladaptation and increases return under future climate

uncertainties. Crowe and Parker (2008) illustrated the analogy for applying portfolio

theory model to support decision-making in planned adaptation to climate change in

reforestation. Just as the market, over time, can value assets differently, so too can climate

under different forecast scenarios create an environment in which different seed sources

are adapted differently to a given site. Thus, the market and the climate both create

uncertainty. Just as portfolio theory is useful in reducing risk under market uncertainties,

so too it can be applied to guide reforestation under future climate uncertainty. The

conceptual framework for the model is presented in Figure 1 below:

Regional Provenance Trials and Site Climate Data

Growth response of populations under different climatic conditions

Species'-Range Impact Model

General Circulation Models

Possible climate scenarios for a given site

Estimates of how well adapted specified populations are to a selected location under a given climate change scenario

Seed source portfolio of populations that minimises the risk of maladaptation across all scenarios for a given site
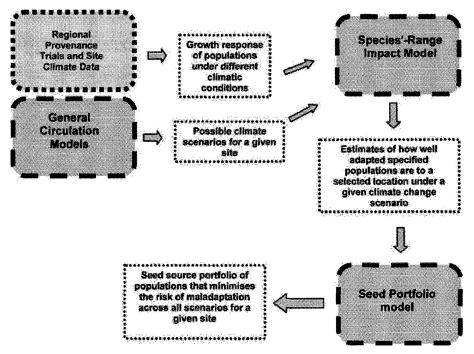
Seed Portfolio model

Fig.1 Model applied for the study (Crowe and Parker 2008)

The Case Study

The present study applied the focal point seed zone method and a simplified version of portfolio modeling approach to select 18 black spruce seed sources that may be suitable for reforestation under future climate uncertainty for three selected sites in Northern and Central Ontario.

Study area

Canada's boreal forest covers a large vegetation zone of the northern latitudes. It stretches across the country, from Yukon in the north, and northern British Columbia in the west to Newfoundland and Labrador in the east. In Ontario, the boreal forest stretches up to the tree line in the far north and into the south of Great Lakes forest of mixed hardwoods and conifers. The average annual temperature within the study area ranges between 2 to -4°C and the average annual precipitation ranges from 600mm – 900mm. The study was conducted in three selected sites across Northern and Central Ontario generally located near Dryden (Lat. 49.92°N, Long. -92.97 °W, Elev. 371m), Kakabeka (Lat. 48.38°N, Long. -89.58 °W, Elev. 270m), and Sault Ste. Marie (Lat. 46.54°N, Long. -84.45°W, Elev. 219m) (Fig. 2, Table 1and Table 2).

Test Establishment

A total of 18 black spruce seed sources predicted to be adapted to future climates were collected from a variety of sources to establish the three field trials. A randomized complete block design was used to establish the tests at each site. Each plot was clearly marked with an aluminum pole at the corner, and tagged with the plot and the seed source numbers.

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Seeds were sown in a Plug Styroblock PSB 309 (60ml plug volume) at the beginning of March 2012, and seedlings were hardened-off before outplanted in the field. Pegging and planting of the seedlings were completed between August and September 2012 at all the test sites. Site preparation was done by spraying and no tending occurred after the planting. Due to scarcity of seed sources and selection procedure not all seed sources predicted to be adaptable for planting equally occurred in all the test locations. The number of seed sources planted at each test location varied but a set of 6 seed sources (6, 8, 9, 17, 18 and 20) were represented at all the test locations (Table 1).
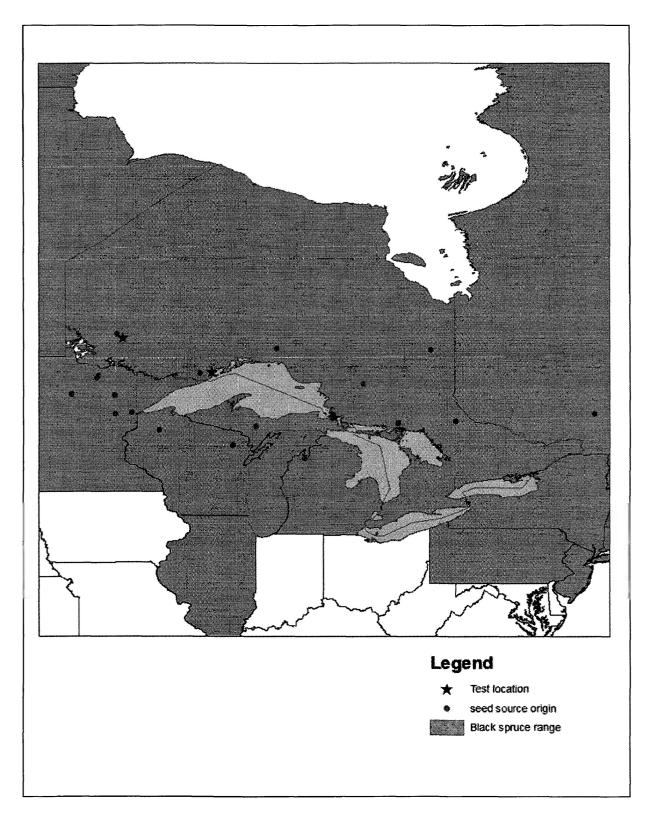
Figure 2: Geographic origin of black spruce seed sources and the test locations

Table 1: Geographic parameters of black spruce seed sources and the planting sites

Agency	seed sources	Seed source Origin	Longitude	Latitude	Planted Locations Dryden	Kakabeka	Sault Ste Marie
CFS	1	St Michel des Saints, QC	-73.880	46.633	×	√	×
CFS	2	North Bay area	-79.450	46.350			
CFS	3	Espanola area	-81.770	46.267			
CFS		Cochrane Uplands 2	-80.470	49.267			
CFS		Chapleau Highlands	-83.170	47.867			
Clergue	6	Algoma Forest	-84.380	46.617			
GreenForest	7	Aster Lake	-86.660	49.328			
USFS	8	Upper Peninsula Michigan	-87.500	46.133			
USFS	9	Northeast Wisconsin	-88.430	45.367			
Greenmantle	10	Lakehead Forest	-89.720	48.317			
USFS	12	Northwest Wisconsin	-91.370	45.983			
USFS	13	Northeast Minnesota	-93.870	48.100			
MN DNR	14	Cloquet, MN	-92.470	46.700			
Lakehead	15	Rosamond Lake	-93.070	49.933			
MN DNR	16	Tamarack, MN	-93.120	46.633			
MN DNR	17	Nashwauk, MN	-93.170	47.383			
MN DNR	18	Big Falls, MN	-93.800	48.183	√	.	
USFS	20	Bemidji, MN	-94.880	47.467	√	√	√

Table 2: Geographic coordinates of test sites

Test	Lat.(dd)	Long. (dd)	Elev. (M)
Dryden	49.92	-92.97	371
Kakabeka	48.38	-89.58	270
Sault Ste. Marie	46.54	-84.45	219

Dryden test

The Dryden test was established with 9 blocks planted with the 12 seed sources in each block as 16 trees per plot (4 x 4 trees). The local seed source (15) was replicated twice in each block. In addition, two mixed plots containing a random mixture of all the seed sources were planted in each block (Fig. 3). The mixed plots were established to compare the growth responses of the selected seed sources in a single seed source plot compared to a mixed plot. A spacing of 1m x 1m was used as a planting distance between each tree. Two border rows were established as buffer along the perimeter of the 9 blocks. This was done to create a more uniform growing environment for the trees, and to minimize edge effects. In total, 2160 trees were planted.

Figure 3: Dryden test plot design

Kakabeka test

The Kakabeka test was established with 9 blocks planted with the 11 selected seed sources in each block as 16 trees per plot (4 x 4 trees). Each block also contained a single random mixed plot of all the seed sources (Fig. 4). A spacing of 1m x 1m was used as a planting distance between each tree. Two border rows were established as buffer along the perimeter of the blocks to minimize edge effects. Seed source (10) is the local source within this test. The total number of trees planted at the test site was 1728.

BLK1 / BLK2 / BLK3

2	20	17	6	12	12	12	12	17	17	17	17	20	20	20	20	18	18	18	18	8	8	8	8	8	8	8	8	6	8	10	1	18	18	18	18
10	9	12	14	12	12	12	12	17	17	17	17	20	20	20	20	18	18	18	18	8	8	8	8	8	8	8	8	17	9	20	2	18	18	18	18
10	1	8	12	12	12	12	12	17	17	17	17	20	20	20	20	18	18	18	18	8	8	8	8	8	8	8	8	20	9	1	8	18	18	18	18
6	9	2	18	12	12	12	12	17	17	17	17	20	20	20	20	18	18	18	18	8	8	8	8	8	8	8	8	14	12	18	10	18	18	18	18
14	14	14	14	20	20	20	20	9	9	9	9	6	14	12	9	17	17	17	17	14	14	14	14	2	2	2	2	17	17	17	17	14	14	14	14
14	14	14	14	20	20	20	20	9	9	9	9	2	10	18	8	17	17	17	17	14	14	14	14	2	2	2	2	17	17	17	17	14	14	14	14
14	14	14	14	20	20	20	20	9	9	9	9	14	1	20	18	17	17	17	17	14	14	14	14	2	2	2	2	17	17	17	17	14	14	14	14
14	14	14	14	20	20	20	20	9	9	9	9	17	6	17	9	17	17	17	17	14	14	14	14	2	2	2	2	17	17	17	17	14	14	14	14
6	6	6	6	2	2	2	2	1	1	1	1	2	2	2	2	6	6	6	6	1	1	1	1	10	10	10	10	12	12	12	12	9	9	9	9
6	6	6	6	2	2	2	2	1	1	1	1	2	2	2	2	6	6	6	6	1	1	1	1	10	10	10	10	12	12	12	12	9	9	9	9
6	6	6	6	2	2	2	2	1	1	1	1	2	2	2	2	6	6	6	6	1	1	1	1	10	10	10	10	12	12	12	12	9	9	9	9
6	6	6	6	2	2	2	2	1	1	1	1	2	2	2	2	6	6	6	6	1	1	1	1	10	10	10	10	12	12	12	12	9	9	9	9
8	8	8	8	18	18	18	18	10	10	10	10	9	9	9	9	12	12	12	12	10	10	10	10	20	20	20	20	6	6	6	6	1	1	1	1
8	8	8	8	18	18	18	18	10	10	10	10	9	9	9	9	12	12	12	12	10	10	10	10	20	20	20	20	6	6	6	6	1	1	1	1
8	8	8	8	18	18	18	18	10	10	10	10	9	9	9	9	12	12	12	12	10	10	10	10	20	20	20	20	6	6	6	6	1	1	1	1
8	8	8	8	18	18	18	18	10	10	10	10	9	9	9	9	12	12	12	12	10	10	10	10	20	20	20	20	6	6	6	6	1	1	1	1

BLK4 / BLK5 / BLK6

9	9	9	9	2	2	2	2	10	10	10	10	8	8	8	8	1	1	1	1	12	12	12	12	17	17	17	17	20	20	20	20	2	2	2	2
9	9	9	9	2	2	2	2	10	10	10	10	8	8	8	8	1	1	1	1	12	12	12	12	17	17	17	17	20	20	20	20	2	2	2	2
9	9	9	9	2	2	2	2	10	10	10	10	8	8	8	8	1	1	1	1	12	12	12	12	17	17	17	17	20	20	20	20	2	2	2	2
9	9	9	9	2	2	2	2	10	10	10	10	8	8	8	8	1	1	1	1	12	12	12	12	17	17	17	17	20	20	20	20	2	2	2	2
12	12	12	12	18	14	8	12	8	8	8	8	2	2	2	2	17	17	17	17	14	14	14	14	1	1	1	1	6	6	6	6	12	2	9	6
12	12	12	12	2	18	6	7	8	8	8	8	2	2	2	2	17	17	17	17	14	14	14	14	1	1	1	1	6	6	6	6	1	14	18	1
12	12	12	12	8	20	9	1	8	8	8	8	2	2	2	2	17	17	17	17	14	14	14	14	1	1	1	1	6	6	6	6	8	12	18	9
12	12	12	12	10	10	9	20	8	8	8	8	2	2	2	2	17	17	17	17	14	14	14	14	1	1	1	1	6	6	6	6	6	20	10	17
20	20	20	20	14	14	14	14	18	18	18	18	6	6	6	6	18	18	18	18	9	9	9	9	12	12	12	12	9	9	9	9	18	18	18	18
20	20	20	20	14	14	14	14	18	18	18	18	6	6	6	6	18	18	18	18	9	9	9	9	12	12	12	12	9	9	9	9	18	18	18	18
20	20	20	20	14	14	14	14	18	18	18	18	6	6	6	6	18	18	18	18	9	9	9	9	12	12	12	12	9	9	9	9	18	18	18	18
20	20	20	20	14	14	14	14	18	18	18	18	6	6	6	6	18	18	18	18	9	9	9	9	12	12	12	12	9	9	9	9	18	18	18	18
6	6	6	6	17	17	17	17	1	1	1	1	20	20	20	20	9	1	9	2	10	10	10	10	10	10	10	10	8	8	8	8	14	14	14	14
6	6	6	6	17	17	17	17	1	1	1	1	20	20	20	20	17	8	12	20	10	10	10	10	10	10	10	10	8	8	8	8	14	14	14	14
6	6	6	6	17	17	17	17	1	1	1	1	20	20	20	20	6	6	12	20	10	10	10	10	10	10	10	10	8	8	8	8	14	14	14	14
6	6	6	6	17	17	17	17	1	1	1	1	20	20	20	20	1	14	2	18	10	10	10	10	10	10	10	10	8	8	8	8	14	14	14	14

BLK7 / BLK8 / BLK9

6	6	6	6	17	17	17	17	2	2	2	2	9	9	9	9	8	8	8	8	17	17	17	17	10	10	10	10	1	8	12	6	17	17	17	17
6	6	6	6	17	17	17	17	2	2	2	2	9	9	9	9	8	8	8	8	17	17	17	17	10	10	10	10	10	14	20	18	17	17	17	17
6	6	6	6	17	17	17	17	2	2	2	2	9	9	9	9	8	8	8	8	17	17	17	17	10	10	10	10	2	9	6	17	17	17	17	17
6	6	6	6	17	17	17	17	2	2	2	2	9	9	9	9	8	8	8	8	17	17	17	17	10	10	10	10	1	8	9	17	17	17	17	17
9	9	9	9	12	12	12	12	8	8	8	8	1	1	1	1	12	12	12	12	6	6	6	6	20	20	20	20	8	8	8	8	18	18	18	18
9	9	9	9	12	12	12	12	8	8	8	8	1	1	1	1	12	12	12	12	6	6	6	6	20	20	20	20	8	8	8	8	18	18	18	18
9	9	9	9	12	12	12	12	8	8	8	8	1	1	1	1	12	12	12	12	6	6	6	6	20	20	20	20	8	8	8	8	18	18	18	18
9	9	9	9	12	12	12	12	8	8	8	8	1	1	1	1	12	12	12	12	6	6	6	6	20	20	20	20	8	8	8	8	18	18	18	18
14	14	14	14	10	10	10	10	1	1	1	1	2	2	2	2	10	10	10	10	18	18	18	18	2	2	2	2	9	9	9	9	14	14	14	14
14	14	14	14	10	10	10	10	1	1	1	1	2	2	2	2	10	10	10	10	18	18	18	18	2	2	2	2	9	9	9	9	14	14	14	14
14	14	14	14	10	10	10	10	1	1	1	1	2	2	2	2	10	10	10	10	18	18	18	18	2	2	2	2	9	9	9	9	14	14	14	14
14	14	14	14	10	10	10	10	1	1	1	1	2	2	2	2	10	10	10	10	18	18	18	18	2	2	2	2	9	9	9	9	14	14	14	14
14	2	18	17	20	20	20	20	18	18	18	18	14	14	14	14	9	17	12	20	20	20	20	20	12	12	12	12	6	6	6	6	1	1	1	1
9	20	12	2	20	20	20	20	18	18	18	18	14	14	14	14	8	14	8	18	20	20	20	20	12	12	12	12	6	6	6	6	1	1	1	1
12	14	1	1	20	20	20	20	18	18	18	18	14	14	14	14	10	6	2	1	20	20	20	20	12	12	12	12	6	6	6	6	1	1	1	1
10	6	8	8	20	20	20	20	18	18	18	18	14	14	14	14	1	17	10	6	20	20	20	20	12	12	12	12	6	6	6	6	1	1	1	1

Figure 4: Kakabeka test plot design

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Sault St. Marie test

The Sault Ste Marie test was established with 9 blocks planted with the 10 selected seed sources in each block as 16 trees per plot (4 x 4 trees). The local seed source (6) is also replicated twice in each block. In addition, each block contained a single random mixed plot of all the seed sources (Fig. 5). A spacing of 1m x 1m was used as a planting distance for the seed sources. A border row was established as buffer along the perimeter of the blocks. In total, 1728 trees were planted.
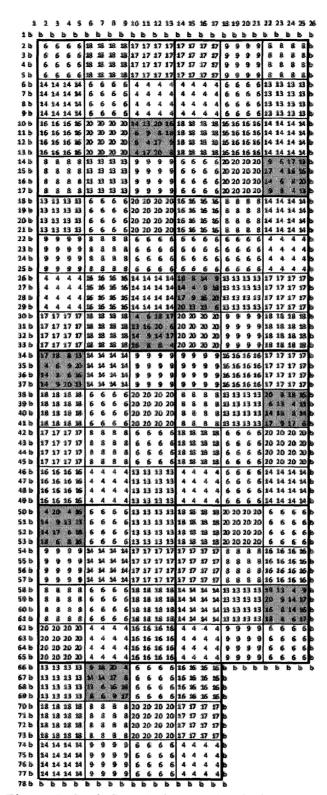
Figure 5: Sault Ste Marie test plot design

Climate data

Regional climate grids (from 1970 to 2000) with a spatial resolution of 10km for the seed sources origin were provided by Dr. Dan McKenney of the Canadian Forestry Service, Great Lakes Forestry Centre (GLFC), Sault Ste. Marie, Ontario. Point values for each seed source origin were determined from the grids. The climate data consisted of 36 climate variables including mean maximum and mean minimum monthly temperatures, and monthly precipitation. ArcGIS 10.1 was used to extract the climate data for individual point locations of the seed sources (Appendix 1).

Data Collection

Field data were collected in the spring and fall field seasons in 2013. Spring heights were measured from May to June, 2013 before bud flush); whereas, fall heights were measured in October, 2013. Spring and fall heights were measured with a measuring pole calibrated in centimeters. Height increments were determined by subtracting spring height from the fall height. Survival was calculated as number of live trees and converted into percentages. The growth variables included were: 2013 fall height, 2013 spring height, and survival.

Statistical Analysis

Since different seed sources were represented at each test location, the analysis was computed separately for each location.

Single Random and Mixed Random Plots Analysis

Prior to analysis, Shapiro and Bartlett tests were performed to check for normality and homogeneity of variance, respectively. All the data met the assumptions (homogeneity and normality), hence there was no transformation. Analysis of variance (ANOVA) in the form of Randomized Complete Block Design (Sokal and Rohlf 1981) was performed to test for statistical differences in growth and survival among seed sources, using a linear model of the form:

$$Yijk = \mu + Bi + \delta i + Pj + E(ij)k \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{Eq. 1}$$

Where; Y_{ij} = the response of ith seedling measured from j^{th} seed source in i^{th} block,

μ = the overall mean,

B_i = the random effect of ith block,

δ_i = the restriction effect of the randomisation of the seed sources treatments within block,

P_j = the random effect of jth seed source origin,

$E_{(ij)k}$ = the random error effect of kth replicates of jth seed source in i^{th} block.

Intraclass Correlation Coefficient (ICC) Analysis

The ICC package in R was used to estimate intraclass correlation coefficient (ICC) (Wolak *et al.* 2012). The ICC estimates the fraction of variation expressed among seed sources (Parker and Van Niejenhuis 1996; Lessser and Parker 2004).

The mathematical formula for ICC is expressed as:

$$ICC = (\frac{\delta^2 \text{provenance}}{\delta^2 Provenance + \delta^2 Block + \delta^2 Prov \, X \, Block + \delta^2 error} x100\% \dots . \qquad \dots . \text{Eq. 2}$$

Regressions and Principal Component Analysis

Simple linear regressions were used to estimate the relationship between the measured growth variables and all the 36 climate variables. This procedure was used to determine whether the variation expressed among seed sources could be predicted by climatic factors. Only climate variables that showed significant values ($p < 0.05$) were retained for further analysis. To be used in determining seed zones, the measured growth responses must be adaptive in nature; thus, the adaptive variation expressed should show correlation with the local climate of the seed source origin (Parker and Van Niejenhuis 1996).

The mean values for the growth responses (spring height, fall height, increment and survival) were analysed using principal component analysis (PCA). Vegan package in "R" was used for the PCA (Jari *et al.* 2013). PCA was used to summarize the main components of adaptive variation in growth responses. Normalized factor scores were calculated for the first three main component axes, and used as new variables to perform multiple regressions against climate variables. The normalized factor scores were estimated by using a weighted average of least significance difference (LSD) values of the original variables (Crowe and Parker 2005). The raw LSD values ($\alpha = 0.05$) for each original variable were determined from the ANOVA output and divided by the standard deviation of the variables to express the LSD as a number of standard deviations. Standardized LSD values for each original variable were then multiplied by the respective variable PCA loadings (absolute value of eigenvectors), summed, and divided by the sum of the absolute loadings again to produce a weighted average LSD. The weighted LSD values were then multiplied by principal components scores to covert the standard deviation values to LSD values (Crowe and Parker 2008).

Using multiple linear regression method, the normalized factors score for each principal component axis were then regressed against the climate variables to determine the combinations of climate variables that best explained the variation in each PCA axis. The regressions equations

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were generated for each PCA axis (Crowe and Parker 2008). All statistical analysis was performed using R-statistical package.

Seed Source and Location Interaction Analysis

Seed source and location interaction were analysed for a set of 6 seed sources (6, 8, 9, 17, 18, and 20) planted across all three test locations using the linear model of the form:

$$Yijk = \mu + Li + Pj + LPij + E(ij)k \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eq. 3$$

Where; Y_{ijk} = the height of ith seedling measured from j^{th} seed source in i^{th} location,

μ = the overall mean,

L_i = the random effect of ith location,

P_j = the random effect of jth seed source origin,

LP_{ij} = the random effect of the ith location with the jth seed source,

$E_{(ij)k}$ = the random error effect of kth replicates of jth seed source in i^{th} location.

RESULTS

Single random plots variation and Intraclass Correlation Coefficients

The analysis of variance showed significant differences (P < 0.05) in each of the observed growth responses among the seed sources at all the test sites (Table 2 and 3). Overall, the Kakabeka test recorded the highest mean spring height of 14.55 cm, whereas, Sault Ste. Marie test had the lowest mean spring height of 12.22 cm. However, mean fall height, mean increment and percentage survival were higher at the Dryden test than the other tests. The Sault Ste. Marie test recorded the lowest in all the growth responses.

Table 3: Grand mean of height, increment, percentage survival, P-value and Intraclass Correlation Coefficient (ICC) of seed sources in single random plots

	Mean	Std. Dev	Min	Max	Range	P value	ICC (%)
Dryden test							
Spring Height (cm)	14.27	2.61	6.00	23.40	17.40	<0.001	29.0
Fall Height (cm)	32.82	6.63	11.00	55.00	44.00	<0.001	18.0
Increment (cm)	18.55	5.53	0.50	39.90	39.40	<0.001	8.0
Survival (%)	97.00	0.17	91.00	100.00	9.00	<0.001	2.0
Kakabeka test							
Spring Height (cm)	14.55	2.40	7.00	25.50	18.50	<0.001	11.0
Fall Height (cm)	32.51	7.20	10.00	55.00	45.00	<0.001	3.0
Increment (cm)	17.96	6.65	0.40	38.50	38.10	<0.001	2.0
Survival (%)	95.00	0.23	90.00	98.00	8.00	0.010	0.7
Sault Ste Marie test							
Spring Height (cm)	12.22	3.95	1.27	30.48	29.21	0.020	3.0
Fall Height (cm)	24.14	5.56	7.62	50.80	43.18	0.010	4.0
Increment (cm)	11.92	3.78	1.27	27.94	26.67	<0.001	1.0
Survival (%)	81.00	0.52	76.00	85.00	9.00	0.050	0.1

Table 4: Ranking of individual seed source mean height, increment and percentage survival of seed sources in single random plots

Seed source	Mean Spring Ht (cm)	Seed source	Mean Fall Ht (cm)	Seed source	Increment (cm)	Seed source	Survival %
Dryden test							
13	16.53	9	37.66	9	22.65	20	100.00
18	15.91	13	36.03	17	20.07	4	99.00
9	15.01	17	35.05	8	19.57	5	99.00
17	14.98	8	34.07	13	19.50	7	99.00
20	14.79	18	34.05	20	19.18	10	99.00
4	14.52	20	33.97	10	18.53	8	98.00
8	14.50	7	32.78	7	18.38	17	98.00
7	14.40	10	32.47	18	18.14	6	97.00
6	14.26	4	32.38	4	17.86	9	97.00
10	13.94	5	31.36	5	17.84	13	97.00
5	13.52	6	31.19	6	16.93	18	97.00
15[#]	11.54	15	27.53	15	15.99	15	91.00
Kakabeka test							
9	15.58	9	35.99	9	20.41	8	98.00
8	15.38	8	34.01	1	19.08	1	97.00
10[#]	15.17	12	33.19	8	18.63	9	97.00
20	15.15	1	32.70	12	18.53	20	97.00
6	14.89	6	32.44	2	18.13	2	96.00
12	14.66	17	31.85	6	17.55	6	96.00
18	14.53	18	31.83	17	17.40	12	94.00
17	14.45	20	31.77	18	17.30	14	93.00
1	13.62	10	31.68	14	17.10	17	93.00
2	13.34	2	31.47	20	16.62	10	91.00
14	13.28	14	30.38	10	16.51	18	90.00
Sault Ste Marie test							
9	13.34	8	26.52	3	13.68	8	90.00
8	13.13	9	26.47	8	13.39	9	85.00
13	12.72	3	26.36	17	×3.33	6	84.00
3	12.68	17	25.71	18	13.28	3	81.00
17	12.38	13	25.69	9	13.13	14	79.00
18	12.26	18	25.54	13	12.97	18	79.00
16	12.25	16	25.11	16	12.86	13	78.00
14	11.73	14	24.24	14	12.51	20	77.00
20	11.49	6	23.62	6	12.49	16	76.00
6[#]	11.13	20	23.31	20	11.82	17	76.00

(# = local sources)

The variation in seed source means (Table 3) indicated that the mean spring height of the Dryden test ranged from 11.54 cm to 16.53 cm. Mean fall height ranged from 27.53 cm to 37.66 cm. Mean height increment ranged between 15.99 cm and 22.65 cm. The Dryden test recorded the highest survival rate compared to the other test sites. Survival across seed sources ranged from 91% to 100%.

Overall, seed source 13 from Northeast Minnesota had the highest mean spring height of 16.53 cm, and seed source 15 from Rosamond Lake (the local source) recorded the lowest height of 11.54 cm. Seed source 9 from Northeast Wisconsin recorded the highest mean fall height of 37.66 cm, whereas seed source 15 recorded the lowest mean fall height of 27.53 cm. For growth increment, seed source 9 from Northeast Wisconsin had the highest increment of 22.65 cm during the growing season. Survival was generally good at the Dryden test. Seed source 20 from Bemidji Minnesota had the highest percentage survival of 100%, whereas seed source 15 recorded the lowest percentage survival of 91%.

Intraclass correlation coefficient (ICC) values presented in Table 3 above ranged from 2% to 29% for the growth responses. The ICC value for spring height was 30%, fall height 18%, increment 8%, and survival 2%.

At Kakabeka test the mean height ranged from 13.28 cm to 15.58 cm for spring height, and 30.38 cm to 35.99 cm for fall height. Mean height increment ranged from 16.51 cm to 20.41 cm. Survival among sources ranged from 90% to 98%. Source 9 from Northeast Wisconsin had the highest spring mean height of 15.58 cm, whereas source 14 from Cloquet, Minnesota had the lowest mean spring height of 13.28 cm. Similarly, seed source 9 had the highest mean fall height of 35.99 cm, whereas seed source 14 recorded the lowest mean fall height of 30.38 cm. For height increment, source 9 recorded the highest growth increment of 20.41 cm, whereas source 10 from Lakehead Forest (the local source) had the lowest increment of 16.51 cm. Seed source 8

from Upper Peninsula Michigan had the highest percentage survival of 98%, and source 18 had the lowest percentage survival of 90%

Intraclass correlation coefficient (ICC) values for Kakabeka test ranged from 0.7% to 11%. The ICC for spring height was 11%, fall height 3%, increment 2%, and survival is 0.7%.

The Sault Ste Marie test recorded mean spring height from 11.13 cm to 13.34 cm, whereas mean fall height ranged from 23.31 cm to 26.52 cm. Seed source 9 from Northeast Wisconsin had the highest mean spring height of 13.34 cm, whereas seed source 6 from Algoma Forest (the local source) recorded the lowest mean spring height of 11.13cm. Seed source 8 from Upper Peninsula Michigan recorded the highest fall height of 26.52 cm and seed source 20 from Bemidji, Minnesota had the lowest fall height of 23.31 cm. Height increment showed seed source 3 from Espanola area had the highest growth increment of 13.68 cm and source 20 recorded the lowest height increment of 11.82 cm. Sault Ste Marie test had the lowest survival compared to other tests. Survival ranged from 76% to 90%. Seed source 8 had the highest percentage survival of 90%, whereas seed sources 16 and 17 recorded the lowest percentage survival of 76%.

Intraclass correlation coefficients (ICC) were relatively lower in Sault St. Marie test than the other tests. The ICC values ranged from 0.1% to 4%. The ICC for spring height was 3%, fall height 4%, increment 1% and survival is 0.1%.

Mixed random plot variation

Results corresponded fairly well for the mixed and separate plots (Table 2 and 4, and Table 3 and 5). The smaller sample size for the mixed plots produced fewer significant differences in height and survival. The analysis of variance for seed sources in mixed random blocks showed significant differences at (P < 0.05) in some of the growth responses that were variable across the three (3) tests (Table 4).

There were significant differences in spring height, fall height and increment but survival was non-significant for the Dryden test, however, the Kakabeka test did not show significant differences in any of the growth responses. The Sault Ste Marie test showed significant differences for fall height and increment, but non-significant differences for spring height and survival. Overall, the Kakabeka test recorded the highest mean spring height of 15.24 cm, mean fall height of 33.78 cm and percentage survival of 99.39%, whereas, the Dryden test recorded the highest mean increment of 18.90 cm. The Sault Ste. Marie test recorded the lowest in all the growth responses with a mean increment of 16.63 cm.

Table 5: Grand mean of height, increment, percentage survival and P value of seed sources in mixed random plots

	Mean	Std. Dev	Min	Max	Range	P value
Dryden test						
Spring Height (cm)	14.68	2.66	7.90	25.10	17.20	<0.001
Fall Height (cm)	33.58	5.88	18.00	52.00	34.00	<0.001
Increment (cm)	18.90	5.23	5.80	37.50	31.70	<0.001
Survival (%)	99.31	1.59	95.65	100.00	4.35	NS
Kakabeka test						
Spring Height (cm)	15.24	2.87	4.00	24.50	20.50	NS
Fall Height (cm)	33.78	7.41	15.00	53.50	38.50	NS
Increment (cm)	18.54	7.04	2.50	36.50	34.00	NS
Survival (%)	99.39	2.01	93.33	100.00	6.67	NS
Sault Ste Marie test						
Spring Height (cm)	12.24	3.70	2.54	22.86	20.32	NS
Fall Height (cm)	25.87	5.59	11.43	40.64	29.21	0.006
Increment (cm)	13.63	4.09	2.54	25.40	22.86	0.003
Survival (%)	93.30	3.66	90.00	100.00	10.00	NS

NS (non-significant at p = 0.05)

Table 6: Ranking of individual seed source mean height, increment and percentage survival in mixed random plots

Seed source	Mean Spring Ht(cm)	Seed source	Mean Fall Ht(cm)	Seed source	Increment (cm)	Seed source	Survival %
Dryden test							
8	17.41	17	38.05	9	23.18	4	100.00
17	16.80	9	37.88	17	21.25	5	100.00
4	15.97	8	36.38	13	19.94	6	100.00
18	15.68	13	34.64	10	19.01	7	100.00
10	14.84	18	34.00	8	18.97	8	100.00
9	14.70	10	33.85	20	18.51	9	100.00
13	14.70	4	33.36	18	18.32	10	100.00
6	14.22	20	32.45	5	18.06	17	100.00
20	13.94	5	31.50	7	17.64	18	100.00
7	13.54	6	31.35	4	17.39	20	100.00
5	13.44	7	31.18	15	17.30	15	96.15
15	11.64	15	28.94	6	17.13	13	95.65
Kakabeka Test							
20	17.86	12	38.19	12	21.88	1	100.00
12	16.31	20	36.09	9	19.99	2	100.00
2	15.73	2	35.64	2	19.91	8	100.00
6	15.54	9	34.78	10	19.32	9	100.00
10	15.06	10	34.38	8	19.23	10	100.00
8	14.85	8	34.08	20	18.23	12	100.00
9	14.79	6	33.07	1	17.68	14	100.00
14	14.74	1	32.18	6	17.53	17	100.00
18	14.52	14	32.09	14	17.35	18	100.00
1	14.50	18	30.83	18	16.31	20	100.00
17	14.12	17	29.28	17	15.16	6	93.33
Sault Ste Marie test							
16	13.83	16	28.93	8	16.27	8	100.00
14	12.91	8	28.89	14	15.67	18	100.00
8	12.62	14	28.58	16	15.10	6	92.86
18	12.49	13	26.44	13	14.32	17	92.86
3	12.42	18	25.4	17	14.26	14	92.31
13	12.12	9	25.05	9	13.04	9	91.67
20	12.12	17	24.52	18	12.91	13	91.67
6	12.07	6	23.77	6	11.70	20	91.67
9	12.01	3	23.42	3	11.00	3	90.00
17	10.26	20	23.09	20	10.97	16	90.00

Individual seed source performance in the mixed random blocks (Table 5) showed, the mean spring height for Dryden test ranged from 11.64 cm to 17.41 cm, whereas mean fall height ranged from 28.94 cm to 38.05 cm. Seed source 8 from Upper Peninsula, Michigan had the highest mean spring height of 17.41 cm, whereas seed source 15 from Rosamond Lake recorded the lowest mean spring height of 11.64 cm. Seed source 17 from Nashwauk, Minnesota recorded the highest mean fall height of 38.05 cm, and seed source 15 had the lowest mean fall height of 28.94 cm. Mean height increment ranged from 17.13 cm to 23.18 cm. Seed source 9 from Northeast Wisconsin had the highest mean increment of 23.18 cm, whereas seed source 6 from Algoma Forest had the lowest mean increment of 17.13 cm. Percentage survival from the Dryden test ranged from 95.65% to 100%. Generally, survival was not much different among seed sources growing in the Dryden test. Seed source 13 from Northeast Minnesota and 15 from Rosamond Lake recorded the lowest percentage survival of 95.65 % and 96.15% respectively.

The Kakabeka test mean spring height ranged from 14.12 cm to 17.86 cm, whereas mean fall height ranged from 29.28 cm to 38.19 cm. Seed source 20 from Bemidji, Minnesota had the highest mean spring height of 17.86 cm, whereas seed source 17 from Nashwauk Minnesota recorded the lowest mean spring height of 14.12 cm. Seed source 12 from Northwest Wisconsin recorded the highest mean fall height of 38.19 cm and seed source 17 from Nashwauk, Minnesota had the lowest mean fall height of 29.28 cm. Mean height increment ranged from 15.16 cm to 21.88 cm. Similarly, Seed source 12 from Northeast Wisconsin had the highest mean increment of 21.88 cm, and seed source 17 from Nashwauk, Minnesota had the lowest mean increment of 15.16 cm. Seed source 6 from Algoma Forest had the lowest percentage of 93.33%.

The Sault Ste Marie test mean spring height ranged from 10.26 cm to 13.83 cm, whereas mean fall height ranged from 23.09 cm to 28.93 cm. Seed source 16 from Tamarack, Minnesota had the highest mean spring height of 13.83 cm, whereas seed source 17 from Nashwauk, Minnesota recorded the lowest mean spring height of 10.26 cm. Again, seed source 16 from

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Tamarack, Minnesota recorded the highest mean fall height of 28.93 cm, whereas seed source 20 from Bemidji Minnesota had the lowest mean fall height of 23.09 cm. For mean height increment, seed source 8 from Upper Peninsula Michigan had the highest mean increment of 16.27 cm and source 20 from Bemidji Minnesota recorded the lowest height increment of 10.97 cm. Survival was generally low in Sault Ste Marie test. Percentage survival ranged from 90 % to 100%. Seed source 8 from Upper Peninsula, and18 from Big Falls, Minnesota had the highest percentage survival of 100 %, whereas seed source 16 from Tamarack, Minnesota, and 3 from Espanola had the lowest percentage survival of 90%.

Seed Sources and Location Interaction

Seed source and location interaction was determined using a set of 6 seed sources (6, 8, 9, 17, 18, and 20) planted across all three test locations. Analysis of variance indicated that sources of variation (seed source, location, source × location) were all significant at $P < 0.05$ for spring height and fall height. However, for survival, seed source variation, and seed source × location interaction were not significant (Table 6).

Mean heights for individual seed sources ranged from 13.04 cm to 14.70 cm for spring heights and 28.13 cm to 33.69 cm for fall heights. Mean increment ranged from 15.09 cm to 18.99 cm. Percentage survival among seed sources ranged from 88.66% to 95.60%. Overall, seed source 9 from Northeast Wisconsin recorded the highest mean spring height of 14.70 cm, mean fall height of 33.69 cm and mean increment of 18.99 cm, whereas seed source 6 from Algoma Forest had the lowest mean spring height of 13.04 cm, mean fall height of 28.13 cm, and mean increment of 15.09 cm. Seed source 8 from Upper Peninsula, Michigan had the highest percentage survival of 95.60%, whereas seed source 18 from Big Falls, Minnesota had the lowest percentage survival of 88.66% (Table 7).

Table 7: ANOVA of the seed sources represented across all test locations

	Df	Mean Sq	P value
Spring height			
Location	2	1974.80	<0.001
Seed sources	5	155.00	<0.001
Seed sources × Location	10	51.30	<0.001
Fall height			
Location	2	19535.00	<0.001
Seed sources	5	1501.00	<0.001
Seed sources × Location	10	154.00	<0.001
Survival			
Location	2	3962.00	<0.001
Seed sources	5	179.00	0.161
Seed sources × Location	10	91.00	0.613

Table 8: Ranking of mean heights and percentage survival of seed sources represented across all test locations

Seed sources	Mean Spring Height (cm)	Seed sources	Mean Fall Height (cm)	Seed sources	Mean Increment (cm)	Seed sources	Survival (%)
9	14.70	9	33.69	9	18.99	8	95.60
8	14.37	8	31.69	8	17.32	9	93.06
18	14.37	17	31.27	17	17.22	6	92.01
17	14.05	18	30.80	18	16.43	20	91.44
20	13.98	20	30.20	20	16.22	17	89.12
6	13.04	6	28.13	6	15.09	18	88.66

Simple linear regressions of growth responses on climate variables

Simple linear regressions of growth responses that showed significant differences among seed sources at ($P < 0.05$) were performed against the 36 climate variables of the seed source origin (Table 8). Seed source means for each growth responses were used for the simple regressions. The independent variables were selected based on Maximal R-square method at significance ($P < 0.05$) but some climatic predictors were significant at ($P < 0.10$). For Dryden test, mean monthly temperatures were the highest predictor values for spring height, fall height and growth increment, whereas precipitation was the highest predictor for survival.

However, for Kakabeka test the r^2 values from the regressions showed mean monthly temperatures were the best predictors for spring height, fall height and survival, whereas precipitation was the best predictor for height increment.

Some climatic predictors selected for Sault Ste Marie test were significant at ($P < 0.10$). For spring height and survival the climatic predictors were mean monthly temperatures, whereas precipitation was the best predictor for fall height and increment.

Table 9: Simple linear regressions of growth responses on climate variables

Dryden test				Kakabeka test				Sault Ste Marie test			
Response	Predictor	R²	P value	Response	Predictor	R²	P value	Response	Predictor	R²	P value
Spring height	octmaxt	0.32	0.050	Spring height	febmaxt	0.21	0.100	Spring height	marmaxt	0.39	0.050
	sepmaxt	0.31	0.050		julprec	0.18	0.100		febmaxt	0.38	0.050
Fall height	octmaxt	0.51	0.010		octmaxt	0.18	0.100		mayprec	0.37	0.060
	marmaxt	0.49	0.010	Fall height	janmaxt	0.48	0.010	Fall height	mayprec	0.28	0.100
	sepmaxt	0.46	0.010		novmaxt	0.48	0.010		febmaxt	0.25	0.100
	febmaxt	0.44	0.010		decmaxt	0.42	0.030		aprmint	0.21	0.100
	aprmaxt	0.40	0.020		febmaxt	0.41	0.030		marmaxt	0.20	0.100
	junmaxt	0.37	0.030		aprprec	0.32	0.050	Increment	julprec	0.26	0.100
	maymaxt	0.34	0.040		marmaxt	0.27	0.050	Survival	janmint	0.79	0.001
	novmaxt	0.34	0.040	Increment	aprprec	0.66	0.001		janmaxt	0.76	0.001
	augmaxt	0.33	0.040		novmaxt	0.66	0.001		febmint	0.75	0.001
	mayprec	0.32	0.050		janmaxt	0.60	0.010		decmint	0.74	0.001
	janmaxt	0.31	0.050		decmaxt	0.59	0.010		decmaxt	0.73	0.001
Increment	marmaxt	0.44	0.010		mayprec	0.56	0.010		novmaxt	0.65	0.004
	febmaxt	0.42	0.020		marprec	0.41	0.030		octmint	0.63	0.005
	mayprec	0.39	0.020		janmint	0.37	0.040		novmint	0.60	0.008
	sepmaxt	0.39	0.020		aprprec	0.37	0.040		sepmint	0.60	0.008
	novmaxt	0.35	0.040		decmint	0.34	0.050		marprec	0.58	0.010
	aprmaxt	0.33	0.040	Survival	decmaxt	0.44	0.020		sepprec	0.57	0.010
	junmaxt	0.32	0.050		novmaxt	0.39	0.030		aprprec	0.56	0.010
	janmaxt	0.31	0.050		novmint	0.39	0.030		novprec	0.50	0.020
	octmaxt	0.05	0.010		janmint	0.33	0.050		febmaxt	0.44	0.030
Survival	mayprec	0.55	0.010		marprec	0.33	0.050		junprec	0.42	0.040
	julprec	0.43	0.020		junprec	0.30	0.050		julprec	0.37	0.060
	decmaxt	0.38	0.030								
	janmaxt	0.38	0.030								
	novmaxt	0.31	0.050								
	aprprec	0.29	0.050								
	decmint	0.28	0.050								
	janmint	0.27	0.050								

Multiple linear regressions and Principal Components Analysis

A combination of Principal Component Analysis (PCA) and multiple linear regressions were used to determine combinations of climate variables and regression models that suitably predicted adaptive variation of black spruce.

Results from principal component analysis for Dryden test (Table 9 and 10) showed, the first two Principal Component (PC) axes explained 90% of the total variation. Principal component axis 1 (PC1) explained 72% of the variation, and Principal component axis 2 (PC2) explained 18% of the total variation. All variable loadings showed strong positive contribution for PC1, while PC2 was positively correlated with survival.

The multiple regression models and independent variables for Dryden test were selected at significant ($P < 0.05$) (Table 11). To avoid multicollinearity "VIF" function in R "car" package was used to estimate Variance inflation Factor (VIF) of the climate variables and Tolerance was calculated from the VIF (Dongyu 2012). Variables with tolerance less than 0.1 was removed (Lesser and Parker 2006). The first PC axis regressions against climate variables showed that October minimum temperature, September maximum temperature and October precipitation correspond to black spruce growth ($r^2 = 0.65$). The second PC axis had an r^2 value of 0.84 and was predicted by the combination of October minimum temperature and October and September precipitations.

Table 10: Eigenvalue, proportion and cumulative of variation from principal components analysis of the Dryden test

	PC1	PC2	PC3
Eigenvalue	2.90	0.70	0.40
Proportion of Variance	0.72	0.18	0.10
Cumulative Proportion	0.72	0.90	1.00

Table 11: Variable loadings, Eigen vectors, Standardised LSD calculations for the principal components axes of the Dryden test

Eigen Vectors	$\alpha = 0.05$ LSD	PC1		PC2	
		loadings	Loadings X LSD	loadings	Loadings X LSD
DrdFHt	0.23	0.97	0.22	-0.22	-0.05
DrdSHt	0.20	0.87	0.17	0.04	0.01
DrdInc	0.23	0.87	0.20	-0.34	-0.08
DrdSuv	0.18	0.65	0.12	0.73	0.13
Sum		**3.37**	**0.71**	**0.21**	**0.01**
Weighted Average			**0.21**		**0.03**

DrdFHt (Dryden fall height); DrdSHt (Dryden spring height); DrdInc (Dryden height increment); DrdSuv (Dryden survival).

Table 12: Multiple regressions of Dryden PC axes seed source scores on climate variables

Dependent variable	Independent variable	Estimate	Std. Error	P > t	Tolerance	P value	R^2
PC1	(Intercept)	-6.257	1.727	0.006		0.020	0.65
	octmint	-0.343	0.138	0.037	0.40		
	octprec	0.018	0.008	0.062	0.59		
	sepmaxt	0.292	0.076	0.004	0.35		
PC2	(Intercept)	0.003	0.036	0.942		0.001	0.84
	octmint	-0.022	0.005	0.002	0.89		
	octprec	0.003	0.001	<0.001	0.39		
	sepprec	-0.002	0.001	0.003	0.39		

Regression models

$$PC1 = -6.257 - 0.343octmint + 0.018octprec + 0.292sepmaxt$$

$$PC2 = 0.003 - 0.022octmint + 0.003octprec - 0.002sepprec$$

The PCA for Kakabeka (Table 12 and 13) indicated the first two Principal Component axes explained 88% of the total variation of the adaptive variation in growth responses; PC1 explained 63% and PC2 25%. All the variable loadings were positively correlated with PC1. In addition, fall and spring heights variable loadings showed positive correlation with PC2. The positive loadings and high coefficients are indication PCI and PC2 axes explained far more of the variation.

The multiple regression models and independent variables for Kakabeka test (Table 14) were selected based on Maximal R-square method at significance ($P < 0.05$). The first PC axis regression with r^2 value of 0.78 showed November maximum temperature, September minimum temperature and September precipitation were strong predictors for black spruce growth and survival. The second PC axis had an r^2 value of 0.82 and was predicted by the combination of November maximum temperature, September minimum and maximum temperatures and May precipitation.

Table 13: Eigenvalue, proportion and cumulative of variation from principal component analysis of the Kakabeka test

	PC1	PC2	PC3
Eigenvalue	2.52	0.99	0.48
Proportion of Variance	0.63	0.25	0.12
Cumulative Proportion	0.63	0.88	1.00

Table 14: Variable loadings, Eigen vectors, Standardised LSD calculation for the principal components axes of the Kakabeka test

Eigen Vectors	α = 0.05 LSD	PC1		PC2	
		loadings	Loadings X LSD	loadings	Loadings X LSD
KKFHt	0.23	0.61	0.14	0.18	0.04
KKSHt	0.21	0.35	0.08	0.81	0.17
KKInc	0.28	0.55	0.16	-0.35	-0.10
KKSuv	0.29	0.46	0.13	-0.43	-0.13
Sum		**1.96**	**0.50**	**0.20**	**-0.01**
Weighted Average			**0.26**		**-0.07**

KKFHt (Kakabeka fall height); KKSHt (Kakabeka spring height); KKInc (Kakabeka height increment); KKSuv (Kakabeka survival)

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Table 15: Multiple regressions of Kakabeka PC axes seed source scores on climate variables

		Estimate	Std. Error	P > t	Tolerance	P value	R^2
PC1	(Intercept)	2.6559	1.2995	0.080		0.009	0.78
	novmaxt	0.5976	0.1361	0.003	0.24		
	sepmint	-0.2601	0.1238	0.073	0.42		
	sepprec	-0.0247	0.0105	0.050	0.39		
PC2	(Intercept)	-0.2128	0.2913	0.492		0.018	0.82
	mayprec	0.0068	0.0019	0.012	0.63		
	novmaxt	-0.0340	0.0172	0.090	0.40		
	sepmaxt	-0.0362	0.0136	0.037	0.67		
	sepmint	0.0664	0.0203	0.017	0.42		

Regressions model

$$PC1 = 2.65 + 0.59novmaxt - 0.26sepmint - 0.02sepprec$$

$$PC2 = -0.21 + 0.01mayprec - 0.03novmaxt - 0.03sepmaxt$$

For Sault Ste Marie test the Principal Component Analysis (PCA) showed the first two

Principal component axes explained 94% of the total variation in growth responses (Table 15 and

16). The first Principal component (PC1) explained 73% of the variation and the second Principal

component (PC2) explained 20%. Principal component 1 (PC1) explained more of the growth

potential as indicated by the positive loadings. Likewise, survival variable loading showed

positive correlation on PC2.

The first PC axis with r^2 value of 0.95 showed April and August precipitations, February

maximum and August maximum temperatures combine as strong predictors for black spruce

growth and survival at the Sault Ste Marie test. The second PC axis had an r^2 value of 0.56 and

was predicted by the September minimum temperature (Table 17).

Table 16: Eigenvalue, proportion and cumulative of variation from principal component analysis of the Sault Ste Marie test

	PC1	PC2	PC3
Eigenvalue	2.93	0.82	0.26
Proportion of Variance	0.73	0.20	0.06
Cumulative Proportion	0.73	0.94	1.00

Table 17: Variable loadings, Eigen vectors, standardised LSD calculation for the principal components axes of the Sault Ste Marie test

Eigen Vectors	$\alpha = 0.05$ LSD	PC1 loadings	Loadings X LSD	PC2 loadings	Loadings X LSD
SMFHt	0.25	0.99	0.24	-0.16	-0.04
SMSHt	0.25	0.94	0.23	-0.08	-0.02
SMInc	0.25	0.90	0.22	-0.23	-0.06
SMSuv	0.10	0.51	0.05	0.86	0.08
Sum		**3.34**	**0.75**	**0.39**	**-0.03**
Weighted Average			**0.22**		**-0.09**

SMFHt (Sault St. Marie fall height); SMSHt (Sault St. Marie spring height); SMInc (Sault St. Marie increment); SMSuv (Sault St. Marie survival)

Table 18: Multiple regressions of Sault Ste Marie PC axes seed source scores on climate variables

Dependent variable	Independent variable	Estimate	Std. Error	P > t	Tolerance	P value	R^2
PC1	(Intercept)	17.6811	2.4427	<0.001		0.001	0.95
	aprprec	-0.0215	0.0060	0.015	0.33		
	augmint	-0.5702	0.1324	0.007	0.50		
	augprec	-0.0740	0.0102	<0.001	0.67		
	febmaxt	0.7910	0.0978	<0.001	0.24		
PC2	(Intercept)	0.9141	0.2863	0.012			
	sepmint	-0.1384	0.0433	0.010	0.63	0.012	0.56

Regression models

$$PC1 = 17.681 - 0.021aprprec - 0.570augmint - 0.074augprec + 0.791febmaxt$$

$$PC2 = 0.914 - 0.138sepmint$$

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DISCUSSION

The understanding of genetic patterns of variation in plant species is critical in moving seed sources across landscapes in the changing climates. This study tested an application of a functional modeling approach to observe early growth responses of black spruce populations predicted to be potentially adaptable for reforestation under future climate uncertainty. While it is too soon to properly evaluate the trial results at this level, the results prove significant variation exists in the growth responses of black spruce seed sources growing under different environmental conditions.

This study found differentiation in fall height, spring height, height increment and survival among the black spruce seed sources. The results also showed that the variation existing among black spruce seed sources is strongly correlated with the climates of the seed sources origin as shown by the coefficient of determination. Similar patterns of variation have previously been reported for black spruce seed weight, germination rate, survival and height, phenology, cold hardiness, and growth (Dietrichson 1969; Morgenstern 1978; Fowler and Park 1982; Nienstadt 1984; Parker *et al.* 1994; Beaulieu *et al.* 2004). These tests were carried out in nursery and environments where site conditions are relatively uniform. The significant variation among populations in adaptive traits such as growth rate, phenology, form and cold hardiness suggests that there exist significant genetic differences among populations. If the pattern of genetic variation tracks the environment or climatic variables of the seed source origins, it provides evidence of natural selection and may be important for adaptation.

Although, survival variation expressed among seed sources was found not to be as strong as for height variation, this result is consistent with the studies of (Nienstadt 1984; Wang *et al.* 1994; 2006). These earlier studies acknowledge that many factors may contribute to plants survival in their early growth. It is probable that herbivorous damage, planting technique, young age of the plants, and insufficient hardening-off of the seedlings before planting all contributed to

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the observed survival. Similar studies also found lack of strong survival differentiation in early growth of boreal conifer species; black spruce (Park and Fowler 1987), white spruce *Picea glauca* (Rweyongeza *et al.* 2007).

The low intraclass correlation coefficient found in this study may be that the seed sources planted have adaptive similarities. Generally, low intraclass correlation coefficient can be explained if there is large component of environmental variation. For instance height growth is highly influenced by the environmental conditions of the test locations rather than genetic (Zobel and Talbert 1984).

The general trend of differentiation in black spruce growth responses as shown by this study confirms many published studies (Morgenstern 1968; 1978; Pollard and Logan 1974; Khalil 1975; Park and Fowler 1987; Johnsen *and* Seiler 1996). These studies indicate, that, like many boreal forest conifer species, black spruce provenances, seed sources and populations exhibit large amount of adaptive genetic variation. Also, that the species' adaptive characteristics strongly correspond to the latitude, longitude and local environmental conditions of the species' ranges. Similarly, Parker and Van Niejenhuis (1992) observed differentiation in phenology and growth traits of black spruce seed sources. Their study also observed the correlation between the black spruce provenances' variation and their local climates, a trend common among many boreal forest tree species. However, in other studies, (Fowler and Mullin 1977) found relatively little differentiation between upland and lowland black spruce. Thus, their study indicated variation in upland and lowland black spruce was not detectable as the seedlings age. Also, Morgenstern (1968) did not find edaphic differentiation in black spruce.

A number of studies have shown existence of edaphic ecotypes in many boreal forest species. The presence of ecotypes were reported in lowland and upland white cedar (*Thuja occidentalis* L) (Habeck 1958), white clover (*Trifolium repens* L) (Snaydon 1962), and white spruce *(Picea glauca (*Moench) Voss) (Farar and Nicholson 1966).

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The results from the present study show clinal differentiation although the patterns do not exactly follow geographic gradient expressed by the origins of the seed sources. Previous studies of black spruce and many boreal conifers species have shown similar irregular patterns of clinal variation (Morgenstern 1968; Rudolph and Yeatman 1982; Rehfeldt 1984; Campbell 1986; Park and Fowler 1988; Joyce 1988; Parker 1992; Parker and Van Niejenhuis 1996). Such patterns of clinal adaptation demonstrated by the seed sources may support the current seed deployment in some Canadian provinces such as Ontario based on the assumption that local sources are best adapted to their current prevailing environmental conditions and their use may prevent maladaptation. However, the projected future changes in temperature and precipitation, if it becomes reality, will not support the present local conditions for future growth (Ledig and Kitzmiller 1992; Papadopol 2000; Kramer and Havens 2009; Hamann *et al,* 2011).

From the present study the local seed sources did not show the best growth in height and survival across the test locations. Consistently, seed sources 9 and 13 from Northeast Wisconsin and Northeast Minnesota respectively, originating from the southerly portions of the study areas showed higher growth across the test locations. This result does not support the inherent assumption that the use of local seed sources in reforestation programmes always reduces the risk of maladaptation, at least in terms of height growth (Rehfeldt 1983; Campbell 1986, Lindgren and Ying 2000;). The study, however, supports the studies of (Parker 1992; Parker *et al.* 1994; Parker and Van Niehenjuis 1996; Lesser and Parker 2006). Their studies showed that seed sources with higher growth were from southwest portion of their sampled area. In many instances, Reich and Oleksyn (2008) also showed that growth varied in the far north between local and other sources, with growth slower for the local sources. Their study found that local sources were only adapted for survival to local conditions, as no geographic pattern of survival was detected.

The scope of climate change and its associated impacts on boreal forest species are major concerns to future genetic resource conservation and reforestation programmes. Compounding the challenges is the uncertainty in future climate estimates. The scenarios for future climates estimates are subjected to many uncertainties as they are based on factors that are not easy to predict over long periods. As a result, the models and technologies to estimate future climates are rather provide conflicting predictions. Different models produce different possible outcomes (McKenney *et al.* 2009; Stankowski and Parker 2010; Stankowski and Parker 2011). For example, Crowe and Parker (2008; 2011) show how white spruce and red pine populations respond differently under different future climate projections in Ontario with the following models; the Canadian GCM (CGCM2), the UK-based Hadley GCM (HADCM3), the Australian-based Commonwealth Scientific and Industrial Research Organisation GCM (CSIROMk2), and the American-based National Centre for Atmospheric Research GCM (NCAR). Similarly, Davis and Zabinski (1991) also show differences among projected ranges of America beech under National Oceanic and Atmospheric Agency (NOAA) and National Aeronautics and Space Agency (NASA) climate models. Such complexity under which multiple seed sources and species respond differently under different future projections makes planned adaptation difficult.

To overcome such problem in reforestation efforts, and conservation of genetic resources, traditional practices such as maintaining species suitable habitats and connecting landscape corridors, or using local seed sources for reforestation, and limiting seeds across zone boundaries have thus far been used as adaptive strategies to either reduce maladaptation, prevent species extinction or extirpation to the changing climates (Rudolph and Yeatman 1982; Park and Fowler 1988; Krosby *et al.* 2010; Aubin *et al.* 2011; Hewitt *et al.* 2011). However, planned adaptation strategies to future climate uncertainty must be innovative, risk-tolerant and perform equally well against all considered future scenarios (Lempert *et al.* 2004; Heller and Zavalata 2009; Hunter *et al.* 2010).

Because many plant species have high genetic diversity, strategies employing diversification have been successful in coping with environmental changes and can be a hedge against future climate uncertainty (Kitzmiller 1976; Hamrick et al, 1979; Ledig and Kitzmiller 1992; Crowe and Parker 2011). In reforestation programmes the best way to use diversity as an adaptive strategy is to mix a set of seed sources (Ledig and Kitzmiller 1992). In such practice at least one or more of the seed sources would be expected to act as a buffer under all plausible future scenarios.

The combination of species range impact model and portfolio optimization model were used in this study to select a set of adaptable seed sources for reforestation in future climate uncertainty. The species-range impact model uses growth responses data to summarise adaptive variation among multiples seed sources growing from different environmental conditions, and make a best match to particular geographic area for optimum growth. This procedure reduces the risk of using maladapted seed sources for regeneration. This approach can be useful for reforestation programmes in many Canadian Provinces where the selection of seed sources for reforestation programmes largely depends on the traditional site region frameworks represented by checker-board pattern of polygons such as (Hills 1961) site region classification in Ontario. These site regions were divided based on administrative districts, geology and soils. This conventional practice of seed transfer has been criticised as it is not based on genecological studies (Rehfeldt 1984; Parker 1992; Lesser and Parker 2006).

Robust solutions are required for planned adaptation to future climate change and that the application of species range impact model, and portfolio optimization model may be a decision tool in selecting adaptable seed sources that can withstand any plausible future climate scenarios.

However, caution should be exercised when applying these models. First, the results from the current study are too early to make any definitive conclusions on the model validity. In addition, like any empirical model they are based on present and future climatic condition

(precipitation and temperature), however plant growth and survival may also be affected by other factors such as physiological, biochemical and biogeographical characteristics of the species range or ecosystem. The other caution to be wary in the use of portfolio model is the biological interpretation of the "risk (the variance and covariance). The only biological interpretation of covariance is that sources that perform well across all scenarios have lower covariance which is difficult to quantify biologically.

FUTURE DEVELOPMENT

The black spruce portfolio trials established across Ontario (Dryden, Kakabeka and Sault Ste. Marie) will serve as long-term tests to study black spruce responses to climate change, and the validity of the species-range impact model and the portfolio optimization model as decision-making tools in planned adaptation to future climate change uncertainty. The presented results are early growth responses of black spruce seed sources growing under different environmental conditions. Therefore, the models will continue to be refined as the tests age. The results from the study will be enhanced by periodic measurement of the tests over time. And as such, it is recommended that in the immediate future, other traits of black spruce including phenology and the root collar diameter should be studied to complement the early growth responses from this study. There was no intent to plant every single source across all test locations; hence, comparing individual seed sources performance across all test locations as well as seed source by location interaction was not possible. Instead, only 6 seed sources (6, 8, 9, 17, 18 and 20) that occurred across all test locations were analysed across planting sites.

CONCLUSION

Challenges associated with climate change have significant impacts on future forest management with far reaching consequences on boreal tree species such as black spruce (Johnston and Williamson 2007; Aitken *et al*, 2008; McKenney *et al*, 2009). The objective of the study was to test the application of a model approach that could provide a robust solution to the anticipated plausible future climate scenarios: the species range impact model and portfolio decision support model. The study finds differentiation in fall height, spring height, height increment and survival among black spruce seed sources growing under the three (3) different environmental conditions. The adaptive variation demonstrated by black spruce corresponds to the present climatic conditions of the seed sources origin. Among climate variables, minimum and maximum temperatures and precipitation in the spring, summer and fall growing seasons were identified as good predictors of black spruce growth at all the test locations. Southern sources originating from Northeast Wisconsin and Northeast Minnesota demonstrated high growth performance across the test locations. This trend gives an indication that southern sources may well be suitable for future reforestation programmes in the Ontario Boreal Forest Region. These early results suggest that the combination of species range impact model portfolio decision support model identify an adaptive pattern of variation from multiple seed sources, and can be used to select a set of sources to succeed under a multiple climate change scenarios and that potentially reduce risk of maladaptation in future climate uncertainty.

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APPENDICES

Appendix 1: Climate values, Latitudes and Longitudes of seed sources origin

seed sources	Longitude	Latitude	aprmaxt	aprmint	aprprec	augmaxt	augmint
1	-73.8833	46.6333	8.1295	-3.7994	71.6900	22.0140	9.5851
2	-79.4500	46.3500	9.0804	-2.1628	65.4592	22.6881	11.5171
3	-81.7667	46.2667	9.4379	-2.2319	65.3567	23.7180	11.1534
4	-80.4667	49.2667	6.3233	-6.6728	45.7791	21.5870	8.6144
5	-83.1667	47.8667	7.3054	-5.5139	53.1798	21.9413	9.3092
6	-84.3833	46.6167	8.1216	-3.0991	65.7587	22.3563	10.7507
7	-86.6603	49.3278	6.2268	-6.0573	41.0486	20.2808	9.0566
8	-87.5000	46.1333	9.2597	-2.0399	60.6615	23.7067	11.8860
9	-88.4333	45.3667	11.7578	-1.9576	69.9758	24.5776	11.5892
10	-89.7167	48.3167	8.7319	-4.7128	49.9553	22.8510	8.8503
11	-91.2167	49.2000	8.2873	-4.6334	34.1780	22.1765	10.2629
12	-91.3667	45.9833	11.5672	-1.8241	58.4504	24.9188	11.7783
13	-93.8667	48.1000	11.5127	-2.1798	41.4672	24.8739	11.3356
14	-92.4667	46.7000	10.5998	-2.0923	49.7437	24.1299	11.7306
15	-93.0667	49.9333	8.6655	-3.8527	34.8273	22.7315	11.2374
16	-93.1167	46.6333	11.5585	-1.8851	48.8956	24.6986	11.7199
17	-93.1667	47.3833	10.9627	-2.6915	44.5432	24.1761	10.9468
18	-93.8000	48.1833	11.6229	-2.2265	41.8443	24.9861	11.2000
19	-93.9167	49.4167	9.6200	-2.9816	33.8043	23.5595	11.7836
20	-94.8833	47.4667	10.9519	-2.2999	39.7085	24.8540	12.0471

Appendix 1 Continued

seed sources	janmaxt	janmint	janprec	julmaxt	julmint	julprec
1	-8.2384	-21.4378	67.1692	23.6607	10.6669	100.0070
2	-7.7003	-18.5823	69.8478	24.4290	12.4779	98.5683
3	-6.0960	-17.3774	63.4649	25.3158	11.9542	64.0027
4	-12.4423	-25.5129	59.4932	23.2869	9.6579	102.7320
5	-9.9749	-22.9338	56.3744	23.4998	10.2809	81.0710
6	-6.2280	-16.4153	80.6125	23.4713	10.6782	84.2837
7	-10.9863	-23.6721	49.1570	20.9756	9.2603	94.5702
8	-5.1624	-15.3009	46.3724	24.9098	12.3695	84.6135
9	-5.5560	-17.4734	33.1300	26.0003	12.4838	91.6727
10	-9.3608	-22.2121	50.9685	24.1744	10.0151	99.1893
11	-12.5154	-24.5774	33.4545	24.0782	11.7659	100.0290
12	-6.9669	-19.3207	29.1859	26.2966	12.9212	118.4060
13	-9.2384	-21.7774	26.7518	25.9930	12.5640	97.5985
14	-7.7045	-19.4586	25.7323	25.4634	12.3186	114.8330
15	-12.8371	-23.8569	29.7176	24.2605	12.5607	97.4510
16	-8.1522	-20.3485	23.0955	25.9660	12.7221	113.9880
17	-9.0485	-21.5940	23.4746	25.3809	12.0835	111.3450
18	-9.1552	-21.7162	28.4813	26.0982	12.4204	94.8625
19	-11.8500	-23.1506	27.3865	24.9766	13.0326	91.9032
20	-9.5171	-22.0389	19.1003	25.8672	13.2416	106.9810

seed sources	augprec	decmaxt	decmint	decprec	febmaxt	febmint	febprec
1	107.7300	-5.1172	-16.6859	74.7003	-5.6533	-20.1238	53.8845
2	96.9446	-4.6402	-14.1694	71.3886	-5.5064	-17.0470	56.2758
3	84.5513	-3.2212	-12.8305	78.8516	-4.3229	-16.1199	47.7495
4	89.7873	-9.4515	-20.5983	62.7853	-9.2559	-23.7384	36.1546
5	81.2311	-6.7038	-17.4262	62.2719	-6.9931	-20.7700	41.9116
6	94.6126	-3.2670	-11.5447	91.3317	-4.4481	-15.6794	49.8794
7	81.2642	-8.1336	-18.9776	49.0428	-8.0801	-21.8480	36.8414
8	92.1735	-2.6519	-11.1866	48.2621	-2.8116	-13.9124	31.4389
9	96.7629	-3.2427	-13.4685	38.8057	-2.3987	-15.2716	24.8233
10	80.6135	-6.5347	-17.7161	51.8003	-5.3635	-18.9200	30.8693
11	92.4744	-9.4410	-20.0992	29.9978	-7.8840	-20.7708	28.8661
12	116.5020	-4.5879	-14.9353	27.3833	-3.0175	-15.9354	22.3948
13	89.6198	-6.9306	-17.5604	25.5990	-4.6279	-17.7475	20.2740
14	100.7590	-5.3285	-15.3465	22.4670	-3.6312	-15.8168	18.0724
15	90.9219	-10.2999	-19.7694	30.5097	-8.0760	-20.1341	22.6801
16	97.9814	-5.7499	-16.0155	19.9640	-3.7055	-16.4621	15.5657
17	93.3527	-6.6415	-17.2144	19.9516	-4.4747	-17.6738	15.8746
18	88.7550	-6.9068	-17.5744	27.5580	-4.5829	-17.7202	21.8015
19	85.6844	-9.3741	-19.0624	26.2177	-7.0582	-19.2726	20.0978
20	91.1449	-6.8778	-17.4895	16.1732	-4.8357	-18.0527	13.3541

Appendix 1 Continued

seed sources	janmaxt	janmint	janprec	julmaxt	julmint	julprec
1	-8.2384	-21.4378	67.1692	23.6607	10.6669	100.0070
2	-7.7003	-18.5823	69.8478	24.4290	12.4779	98.5683
3	-6.0960	-17.3774	63.4649	25.3158	11.9542	64.0027
4	-12.4423	-25.5129	59.4932	23.2869	9.6579	102.7320
5	-9.9749	-22.9338	56.3744	23.4998	10.2809	81.0710
6	-6.2280	-16.4153	80.6125	23.4713	10.6782	84.2837
7	-10.9863	-23.6721	49.1570	20.9756	9.2603	94.5702
8	-5.1624	-15.3009	46.3724	24.9098	12.3695	84.6135
9	-5.5560	-17.4734	33.1300	26.0003	12.4838	91.6727
10	-9.3608	-22.2121	50.9685	24.1744	10.0151	99.1893
11	-12.5154	-24.5774	33.4545	24.0782	11.7659	100.0290
12	-6.9669	-19.3207	29.1859	26.2966	12.9212	118.4060
13	-9.2384	-21.7774	26.7518	□5.9930	12.5640	97.5985
14	-7.7045	-19.4586	25.7323	25.4634	12.3186	114.8330
15	-12.8371	-23.8569	29.7176	24.2605	12.5607	97.4510
16	-8.1522	-20.3485	23.0955	25.9660	12.7221	113.9880
17	-9.0485	-21.5940	23.4746	25.3809	12.0835	111.3450
18	-9.1552	-21.7162	28.4813	26.0982	12.4204	94.8625
19	-11.8500	-23.1506	27.3865	24.9766	13.0326	91.9032
20	-9.5171	-22.0389	19.1003	25.8672	13.2416	106.9810

Appendix 1 Continued

seed sources	junmaxt	junmint	junprec	marmaxt	marmint	marprec
1	21.2330	8.0154	105.1910	0.8088	-12.9991	64.6734
2	21.8372	9.7387	89.7108	0.8300	-10.6575	66.7794
3	21.9681	8.7108	66.3129	1.1959	-10.3894	66.1008
4	20.7161	6.4951	88.9034	-2.2940	-16.5411	53.6585
5	20.8530	7.3770	85.9375	-0.7503	-14.3458	57.6795
6	20.6529	7.6441	85.4747	0.7173	-10.5168	61.2611
7	18.6746	6.4487	88.3175	-1.6810	-15.1490	42.0009
8	22.1885	9.3756	83.1942	2.2402	-8.6070	56.7314
9	23.9587	9.6518	94.6711	3.5292	-8.9592	53.8003
10	21.2352	6.7955	91.1905	0.5496	-12.4899	44.6624
11	21.0062	8.6091	99.6738	-0.6852	-13.7536	33.6914
12	24.0099	9.8402	101.7650	3.0738	-8.9203	44.3840
13	23.6461	9.9224	113.4830	2.3433	-10.2388	29.1624
14	22.8625	8.7888	108.6000	2.2462	-9.0895	37.7334
15	21.5732	9.6384	102.5870	-0.6345	-12.9551	31.3657
16	23.7864	9.7634	111.0670	2.6814	-9.2893	34.1642
17	23.2550	9.3657	113.0870	2.1031	-10.4104	29.1519
18	23.7037	9.7780	115.5150	2.4086	-10.2191	29.8377
19	22.1802	10.1275	104.2490	0.2316	-11.8105	27.5178
20	23.5068	10.6631	102.0420	1.8327	-10.3902	27.9023

Appendix 1 Continued

seed sources	maymaxt	maymint	mayprec	novmaxt	novmint	novprec
1	16.9202	2.9791	91.8658	1.9614	-6.6036	84.7567
2	17.5020	4.8873	86.5061	2.5614	-4.8089	83.0887
3	17.5051	4.1305	75.6889	3.6111	-3.9763	80.0259
4	15.2417	1.2591	69.1173	-0.7537	-8.6756	63.6631
5	16.5533	2.4743	82.7024	0.4596	-7.4308	63.5609
6	16.2755	3.1799	72.8926	2.9339	-4.3183	88.8086
7	14.3807	1.6281	69.4803	-0.7281	-8.8895	63.7337
8	17.2996	4.2166	74.8860	3.7639	-4.3300	68.3277
9	19.7719	4.4396	85.5363	3.7632	-5.7991	59.5735
10	17.0207	1.8019	69.8288	1.0450	-8.2963	62.5853
11	17.1756	3.2410	65.8995	-1.3398	-9.3352	42.0063
12	19.6832	4.6870	84.9779	2.9033	-6.2646	53.3347
13	19.6844	5.0270	71.6007	0.8361	-7.9206	42.2864
14	18.2992	3.9102	74.2982	2.1044	-6.6516	47.6082
15	17.3121	4.1293	61.2952	-1.7735	-8.9716	41.8104
16	19.3722	4.6793	75.9537	2.0094	-7.0007	42.3782
17	18.9866	4.2043	72.1085	1.0063	-7.9767	38.4249
18	19.8443	4.9495	71.7983	0.8608	-7.9403	44.3765
19	17.8803	4.7064	60.5562	-0.7354	-8.2692	42.0637
20	19.1134	5.2749	69.3243	0.8495	-8.2250	31.1231

Appendix 1 Continued

seed sources	octmaxt	octmint	octprec	sepmaxt	sepmint	sepprec
1	9.3232	-0.3116	89.7127	16.3450	5.1321	100.4970
2	10.3543	1.3728	90.8534	17.1130	7.0140	107.6350
3	11.2084	1.6893	95.8845	18.0987	6.9285	93.3668
4	7.8433	-0.8509	78.0402	15.0760	4.2215	105.4840
5	8.8717	-0.4013	75.3494	15.5891	4.6554	93.3094
6	10.5956	1.4875	97.5238	17.2384	6.8112	104.3380
7	7.4553	-0.7390	84.1394	14.3391	4.5241	101.1840
8	12.1366	1.9737	79.4521	18.7832	7.4702	94.8310
9	12.9474	0.7900	66.2700	19.4021	6.7040	97.5033
10	10.2538	-0.8353	74.0196	17.0890	4.2829	95.6742
11	8.4484	-0.2250	69.3538	15.5176	4.9097	95.5034
12	12.9545	0.8190	74.3343	19.6223	6.7419	103.9790
13	11.6072	0.4892	60.6856	18.7047	6.2024	79.7019
14	12.0239	0.9765	61.4666	18.8427	6.8262	89.1313
15	8.3566	0.1345	55.3102	15.8497	5.7480	89.7495
16	12.3307	0.6663	62.5320	19.2350	6.6335	81.4200
17	11.3719	0.0808	62.7909	18.4026	5.8990	82.7915
18	11.6340	0.4552	60.0012	18.7709	6.1024	80.7930
19	9.5823	0.7046	53.8096	16.9264	6.2817	80.8336
20	11.7564	0.2965	63.1266	18.8462	6.4598	71.3783