Climatic Adaptation of White Spruce and Lodgepole Pine in Alberta Controlled Parentage Programs

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Contents

1.0 Background

Forest tree species, like most wide-ranging plant species, consist of locally adapted populations that are matched to a variety of climatic and edaphic environments where they naturally occur (e.g., Kawecki and Ebert 2004; Savolainen et al. 2007). Accordingly, the health, productivity, and wood quality of managed forests greatly depend on trees' being well adapted to the environmental conditions that occur at planting sites. Successful reforestation programs therefore require planting stock that is both sufficiently genetically diverse and genetically well adapted to the target environment.

Throughout Alberta, tree populations predominantly show clinal patterns of adaptation to different macroclimatic conditions (Rweyongeza et al. 2007a, 2007b; 2010). Replicated provenance and progeny field trials have been used to relate tree characteristics such as growth and phenology to environmental characteristics (see Rweyongeza et al. 2010)). Further, these experiments have been used for extensive testing and selection of planting stock by the province's industry and government agencies to maintain tree improvement programs for white spruce, black spruce, lodgepole pine, Douglas-fir, tamarack, and trembling aspen. For each species program, seed is collected from, and planting stock is developed for, different physiogeographic regions within Alberta, known collectively as the controlled parentage program (CPP) regions.

Currently, provincial regulations direct that planting stock must be deployed within its region of origin to prevent loss of productivity or poor forest health due to maladaptation. However, this strategy may be problematic in the future as climate change will likely cause a mismatch between the climatic conditions of the CPP region planting environment, and those which the CPP region planting stock is adapted to. For example, Alberta recently experienced a warming trend of 0.8°C and a precipitation reduction of approximately 10% over a 25-year period (Mbogga et al. 2009). Reciprocal transplant experiments have shown that this climate shift has led to suboptimal growth due a substantial mismatch between local populations and the environments in which they occur. Such maladaptation contributes to loss of forest productivity and forest health, which has also been well documented in Alberta (Hogg et al. 2008; Michaelian et al. 2010).

In 2012, the Climate Change and Emission Management (CCEMC) Corporation launched the Tree Species Adaptation Risk Management (TSARM) project to assist the province in developing public policies on climate change adaptation through Alberta tree improvement programs. The project implemented a number of subprojects within government, industry, and government-industry cooperative tree improvement programs (CPP regions), which were designed to generate information needed to support public policy on transfer of reforestation seed across the province. The primary tool of adaptation to climate change in artificially regenerated forests is the choice of the seed source and its allocation to a proper planting site. Therefore, understanding the climatic pattern of the province, its relationship with the population genetic pattern of the tree species, and how this relationship would change in a changing climate is a prerequisite in developing evidence-based climate change adaptation policy. At an individual CPP level, prediction of climatic change dynamics would enable the program owners to reorganize their programs by introducing parent trees and populations with greater climatic plasticity. Understanding the relationships between CPP regions would enable programs to share parent trees and seed, and coordinate field experiments with benefits across programs, thereby improving program efficiency, which would increase the ability and willingness of forest companies to integrate climate change adaptation with their primary economic program objectives.

The subproject that is the subject of the present report was undertaken to answer the following questions:

- How climatically different are the CPP regions in the current and projected future climate?
- Which of the CPP regions can share seed in part or whole?
- If climate change occurs as projected, how can the CPP regions be reorganized?
- If the CPP regions need to lower the risk level posed by the genotypic composition of their programs, where do they need to sample to capture genotypes that are better adapted to climatic limitations of the future (e.g., drought)?

The project addresses the concerns of the impact of climate change on survival, growth, productivity, and health of commercial forest tree species in Alberta from the quantitative genetics and climatic modelling point of view. Inferences from this work will be integrated into seed and clonal transfer guidelines for CPP material. In addition, results from this work will be used to re-evaluate and potentially reconfigure the CPP regions in light of the projected changes in the province’s climate.

White spruce and lodgepole pine make up about 80% of all trees planted in Alberta annually. Therefore, adequately addressing climate change adaptation for forestry in Alberta requires a careful examination of white spruce and lodgepole pine breeding in individual CPP programs and across programs. This report is a compressed version of a comprehensive climatic and genetic analysis of the two species; more technical presentation of the analytical methodologies will be published in the peer-reviewed journals. Throughout this report, “CPP” and “breeding region” may be used interchangeably to mean the same thing.

2.0 Climate Change Risk management for Commercial Tree Improvement Programs in Alberta

The main objectives of this project were to summarize information and develop tools to aid the development of seed-transfer guidelines for reforestation practices under climate change. Genetic analysis of controlled parentage program (CPP) trial data and climatic summaries have been synthesized to develop holistic summaries of the white spruce (*Picea glauca*) and lodgepole pine (*Pinus contorta*) CPP programs in Alberta. The final results for each species are provided respectively in the following subsections. Each set of results is currently being developed into individual species-specific manuscripts for scientific publication in a peer-reviewed journal in 2015.

Results 1: Synthesized Results for White Spruce

1.1 Summary of Genetic Information and Seed Transfer

The white spruce CPP is the largest in the province, encompassing a total area of approximately 275,816 square kilometres dominated by mixedwood forest types (Figure 1). This area is divided into nine individual regions identified as CPP regions D, D1, E, E1, E2, G1, G2, H, and I; however, there are boundary overlaps between regions D, D1 and I, as well as between E and E1. In Figure 1, different colours identify the regions, with the overlaps illustrated by the outlines in the region's corresponding colour. Given that there are no improvement programs for the overlap regions themselves, experimental site locations and collection origins that fall within an overlap between regions are used to establish seed-transfer guidelines for multiple regions for this project. For example, the white spruce collection identified as accession number 1958 originates in a low-elevation central mixedwood ecosystem in the E-E1 overlap area and was tested at the single experiment site at Hay River in CPP region H. The performance of this collection in CPP region H would count toward both the general performance of material from CPP regions E and E1.

Trial Series	Year Planted	Number of Sites	Number of Parents	Evaluation Year
Progeny test series				
G132	1986	4	150	16
G133	1988	3	131	24
G135	1988	2	73	21
G156	1994	3	70	18
G157	1994	3	61	18
G231	1986	1	18	30
G347	2000	2	88	10
G352	2001	3	137	10
G354	2001	5	301	14
G357	2002	2	79	7
Provenance test series				
G103	1981	11	86	32
G276	1993	4	23	17
G277	1993	1	40	17
G325	1997	1	49	15
G332	1999	1	73	12
G366	2005	2	53	7

Table 1. Summary of white spruce progeny and provenance trials.

Table 1 outlines the 16 progeny and provenance trial series that were evaluated in this project. Within these trial series, sites located outside Alberta's CPP regions were not included in the analysis. In total, 133,791 individual trees tested within 44 individual experiments at 24 geographic locations were evaluated (Figure 1). Although this project addresses the white spruce Controlled Parentage Program, Engelmann spruce and interior spruce trees were included in the analyses. Given that these species often occur jointly and hybridize in natural stands, the inclusion of the additional species is appropriate. For each test installation, recorded locations were extracted from establishment reports provided by Alberta Environment and Sustainable Resource Development (ESRD). The recorded values were confirmed against satellite imagery that showed the planting sites (Google Earth), and elevation values were then cross-checked against digital elevation models at both 25- and 250-metre resolution. Discrepancies were resolved though consultation with Leonard Barnhardt (ESRD), who has personal knowledge of all of the planting sites.

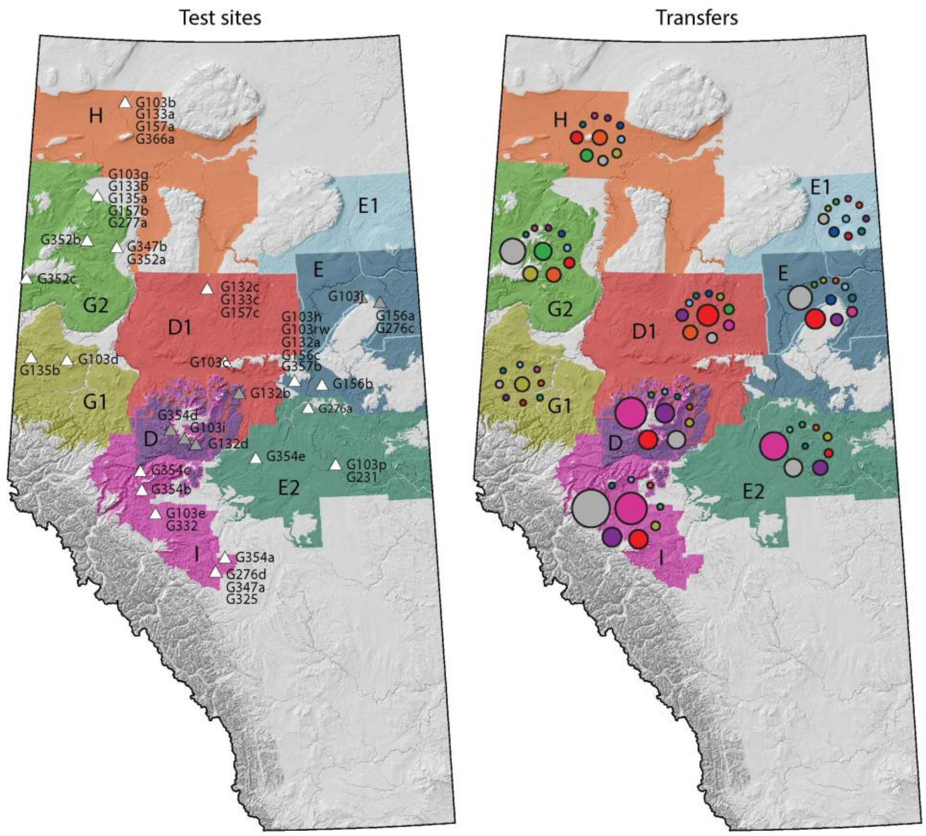


Figure 1. Delineations and transfers among Alberta's white spruce CPP regions. For regions that overlap (D, D1, and I, and E and E1) the overlap boundaries are defined by the region outline of the same colour. Test sites that fall within each region are presented as Δ with test sites that occur in an overlap between adjacent CPP regions coloured grey. For each site, the trial series tested are identified with the trial series test number (e.g., G103b). For the map of transfers, the size of the circles proportionally reflects the number of unique parents originating from within each coloured CPP region respectively.

The origin breakdown for the parents tested within each CPP region is illustrated in Figure 1 with the size of the transfer circles proportionally reflecting the number of transfers across all CPP regions. In almost all regions, the greatest numbers of parents tested originate from locations outside the network of white spruce CPP regions (identified in grey), revealing the larger study of seed performance the trial series were originally established for. The number of seed transfers among the CPP regions ranges between 0 and 220 unique parents, with higher numbers of parents tested often originating from an adjacent CPP region. Transfers of seed beyond CPP regions adjacent to the region of origin are limited, mostly reflecting less than 10 unique parents. For example, there are very few seed transfers of material originating in the eastern CPP regions E (dark blue), E1 (light blue), and E2 (teal) to other areas.

1.2 Climatic Summary of the White Spruce CPP Regions

The climatology of Alberta's white spruce CPP regions is related to their proximity within Alberta's natural regions and sub-regions, and primarily driven by a latitudinal temperature gradient and precipitation patterns that are related to regional topography. The range of mean annual temperature and mean annual precipitation for each white spruce CPP region at one-kilometre resolution, along with the climate for each experimental test site that falls within the region, are illustrated in Figure 2. Test sites that occur in overlapping CPP regions are represented by a grey triangle corresponding to Figure 1. CPP regions D (purple) and I (pink) represent ecosystems in the Rocky Mountain Foothills. These CPP regions experience the greatest amount of annual precipitation (500–700 mm), but they both have a narrow range of mean annual temperature (1–3°C). A similar temperature trend is observed in the CPP region G1 (light green) which lies adjacent to the northern boundary of region I (Figure 1). However, there is significantly more variation in mean annual precipitation within this region, reflecting the precipitation characteristics of the Rocky Mountain Foothills, dry mixedwood forest, and Peace River parkland ecosystems that lie within the region's boundary. CPP region E2 (teal) represented a transition zone between the wetter central mixedwood forest and the drier parkland and grassland ecosystems of southern Alberta. The remaining CPP regions represent boreal forest ecosystems with temperature variation increasing with latitude.

For most CPP regions, performance of material in experimental tests can aptly be extended to the region as a whole, as test sites' climates are a moderate to good representation of the climatic range of the region. CPP region H is an exception as it only has a single experimental test site within the region. Moreover, two test sites that are climatically similar rather than representing the larger range of the region represent CPP regions G1 and E1. Note that this project only includes a subset of all experimental test sites within each region where data was available. Recently established sites with young trees that could potentially fill the climate gaps would therefore not be included in this project or in Figure 2. In the future, additional data could revise results from this project.

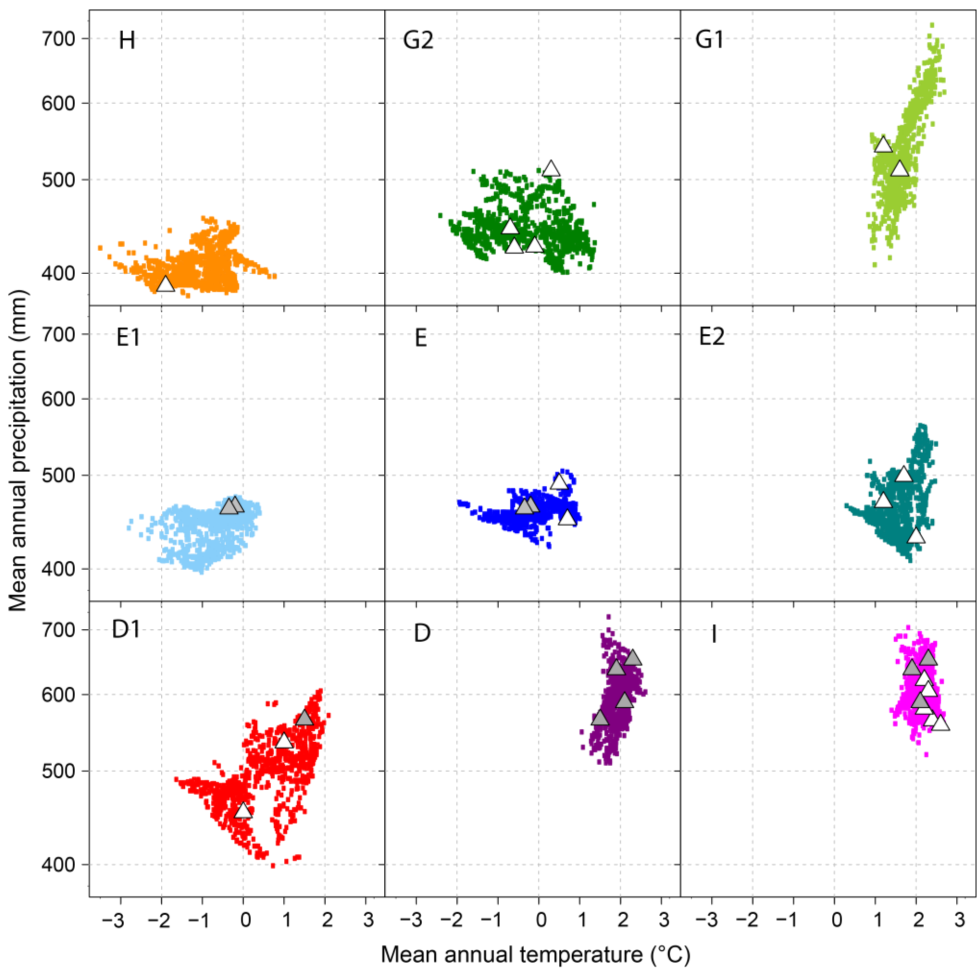


Figure 2. Summary of the mean annual precipitation over the mean annual temperature for each of Alberta's white spruce CPP regions. Coloured points represent the range of climate at one-kilometre resolution for each region. The climates of each test site are also provided as Δ. Test sites that occur in an overlap between adjacent CPP regions are coloured grey.

1.3 Estimated Relative Performance of Seed Material under Transfer

An important component of the overall analyses of the CPP is to determine whether any of the current stock of parent material will likely perform poorly under expected climate projections for Alberta. If so, the poorly performing parents should be removed from the acceptable planting stock or only cautiously used in environments where they are currently adapted and will remain adapted in the future.

As a first step, general parent performance after transfer between CPP regions was estimated. Relative performance (i.e., the number of standard deviations away from the mean) of each parent in each trial experiment (e.g., G132a) was initially calculated using a mixed-model approach summarized over REP for the randomized complete block design trials, and BLOCK then REP for the alpha design trials (G354 series only). Outputs from the mixed models represent best linear unbiased estimates (BLUEs) of the (co) variance parameters representing relative performance, and their associated standard errors. The standard errors associated with each BLUE provide a measure of uncertainty for the performance of transferred seed material, with larger values indicating a greater range of performance. Once performance for each parent was determined for a trial, a second mixed model incorporating the parent's origin CPP region, the test site CPP region, and their interaction as fixed effects was executed. These estimates of the fixed effects for origin CPP × site CPP were then adjusted using local transfer estimates (e.g., the performance of CPP region D material at test sites within the local region) to reflect relative performance of material when transferred compared to the local stock. All mixed-model analyses were executed by using the average information REML algorithm implemented in the ASREML software (Gilmour et al. 1995, Biometrics: 1440-1450) implemented with the R programming language (R Development Core Team, 2012, R Foundation for Statistical Computing, Vienna, Austria).

Estimates of relative performance (i.e., standard deviations away from the local) for white spruce material under transfer, including the standard error of the estimates, is presented in Table 2. Values along the diagonal representing local transfers are set to zero, and values under seed transfer indicate whether relocated seed performed worse (i.e., negative) or better (i.e., positive) than the local stock. Relative performance of transferred material is further illustrated in Figure 3, where red and green arrows indicate worse- and better-performing material, respectively, and the width of the arrow indicates the magnitude of performance. Further, Figure 4 presents the shifts in both the mean annual temperature (°C) and growing season precipitation (mm), compared to the estimated performance of seed material under transfer between the CPP regions (Table 2).

Results suggest seed performance under transfer appears to be tightly linked to available precipitation. Seed originating in warm and wet Rocky Mountain Foothills ecosystems was found to outperform local sources in adjacent wet boreal ecosystems (e.g., from CPP region I to D1, Figures 3 and 4), but these sources underperformed when transferred longer distances into drier boreal ecosystems where growing season precipitation was reduced by more than 150 mm (e.g., from CPP region D to H, Figures 3 and 4). Moreover, within boreal ecosystems, lateral transfers west from equivalent or drier ecosystems perform well in wetter environments (e.g., from CPP region E1 to D1, Figures 3 and 4). Alternatively, the opposite trend was observed for eastern transfers from wet to drier ecosystems within the boreal (e.g., from CPP region H to E, Figures 3 and 4). Interestingly, seed from adjacent southern regions often outperformed local sources when transferred north into slightly colder environments (e.g., from CPP region E2 to E, Figures 3 and 4), suggesting the local sources in these regions may be suffering maladaptation. All southern transfers were found to be disadvantageous, which could indicate potential reductions in tree performance as warmer temperatures in Alberta are projected to shift northward under climate change projections.

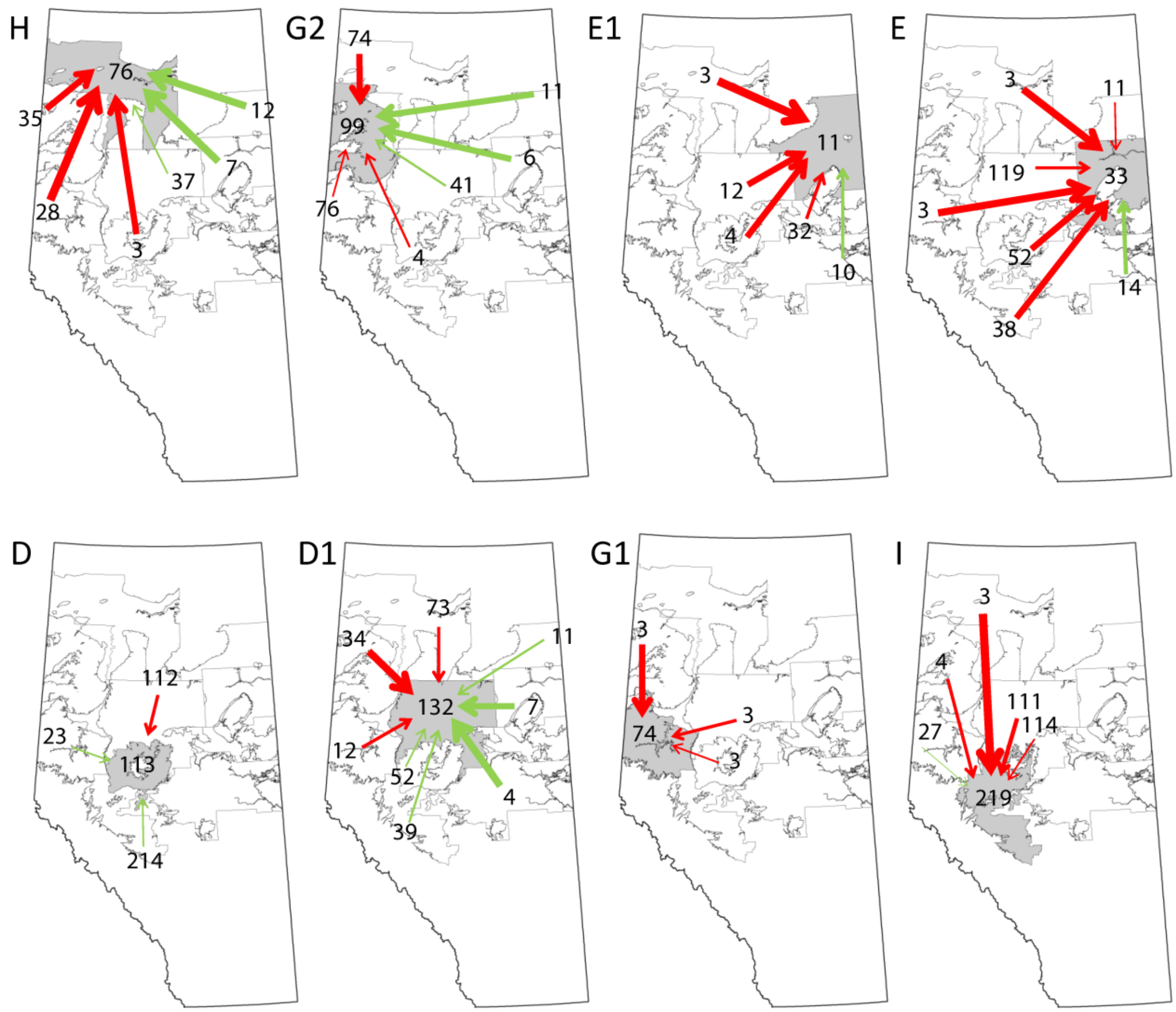


Figure 3. Illustration of the relative performance of CPP seed material when tested within the local and alternate regions, with red and green arrows representing below- and above-average performance compared to the local populations, respectively. The width of the arrows represents the magnitude of performance provided in Table 3. The number of unique parents that relative performance is calculated from is also provided.

To\From	D	D1	E	E1	E2	G1	G2	H	I
D	0 (0.13)	-0.33 (0.13)	No Data	-1.15 (0.72)	-0.6 (0.56)	0.07 (0.2)	-0.43 (0.7)	-0.36 (0.43)	0.03 (0.12)
D1	0.12 (0.14)	0 (0.13)	0.52 (0.33)	0.21 (0.29)	0.72 (0.43)	-0.41 (0.25)	-0.78 (0.2)	-0.38 (0.18)	0.12 (0.15)
E	-0.47 (0.21)	-0.29 (0.2)	0 (0.21)	-0.01 (0.24)	0.18 (0.26)	-0.89 (0.4)	-0.47 (0.46)	-0.82 (0.32)	-0.49 (0.22)
E1	-0.62 (0.39)	-0.6 (0.26)	-0.22 (0.23)	0 (0.29)	0.28 (0.32)	-0.57 (0.71)	-0.55 (0.54)	-0.93 (0.38)	-0.38 (0.51)
E2	0.44 (0.24)	0.32 (0.27)	No Data	1.17 (0.75)	0 (0.59)	0.73 (0.28)	-0.36 (0.56)	0.02 (0.39)	0.42 (0.23)
G1	-0.14 (0.49)	-0.16 (0.49)	No Data	-0.89 (0.77)	-0.3 (0.78)	0 (0.31)	-0.51 (0.49)	-0.41 (0.58)	-0.17 (0.56)
G2	-0.12 (0.35)	0.17 (0.2)	0.51 (0.33)	0.55 (0.28)	-0.24 (0.57)	-0.12 (0.2)	0 (0.18)	-0.47 (0.21)	-0.01 (0.43)
H	-0.54 (0.49)	0.02 (0.31)	0.81 (0.41)	0.69 (0.37)	-0.4 (0.78)	-1.13 (0.32)	-0.49 (0.31)	0 (0.3)	-0.42 (0.56)
I	-0.06 (0.12)	-0.44 (0.13)	No Data	-0.86 (0.45)	-0.66 (0.37)	0.04 (0.16)	-0.36 (0.34)	-0.92 (0.28)	0 (0.12)

Table 2. Best linear unbiased estimates indicating the relative performance of seed under transfer among Alberta's white spruce CPP regions. Values indicate the number of standard deviations below (negative) or above (positive) the average performance of local material from the CPP region. The standard error for estimates is presented to provide a measure of uncertainty in performance estimates over seed material of a common origin CPP. Values that are calculated with less than three populations under transfer are greyed, and not illustrated in Figure 3.

a) Mean annual temperature (°C)

Test sites	Difference in MAT (°C) from source to site climate								
	H	E1	G2	E	D1	E2	G1	D	I
H	-0.1	-1.9	-1.7	-2.1	-2.4	-2.7	-3.2	-3.8	-3.9
E1	1.3	-0.5	-0.3	-0.7	-1	-1.3	-1.8	-2.4	-2.5
G2	1.4	-0.4	-0.2	-0.6	-0.9	-1.2	-1.7	-2.3	-2.4
E	1.6	-0.2	0	-0.4	-0.7	-1	-1.5	-2.1	-2.2
D1	2.2	0.4	0.6	0.2	-0.1	-0.4	-0.9	-1.5	-1.6
E2	3.4	1.6	1.8	1.4	1.1	0.8	0.3	-0.3	-0.4
G1	3.4	1.6	1.8	1.4	1.1	0.8	0.3	-0.3	-0.4
D	3.7	1.9	2.1	1.7	1.4	1.1	0.6	0	-0.1
I	3.8	2	2.2	1.8	1.5	1.2	0.7	0.1	0

Test sites	Performance of transferred sources relative to local								
	H	E1	G2	E	D1	E2	G1	D	I
H	0 (0.3)	0.69 (0.37)	-0.49 (0.31)	0.81 (0.41)	0.02 (0.31)	-0.4 (0.78)	-1.13 (0.32)	-0.54 (0.49)	-0.42 (0.56)
E1	-0.93 (0.38)	0 (0.29)	-0.55 (0.54)	-0.22 (0.23)	-0.6 (0.26)	0.28 (0.32)	-0.57 (0.71)	-0.62 (0.39)	-0.38 (0.51)
G2	-0.47 (0.21)	0.55 (0.28)	0 (0.18)	0.51 (0.33)	0.17 (0.2)	-0.24 (0.57)	-0.12 (0.2)	-0.12 (0.35)	-0.01 (0.43)
E	-0.82 (0.32)	-0.01 (0.24)	-0.47 (0.46)	0 (0.21)	-0.29 (0.2)	0.18 (0.26)	-0.89 (0.4)	-0.47 (0.21)	-0.49 (0.22)
D1	-0.38 (0.18)	0.21 (0.29)	-0.78 (0.2)	0.52 (0.33)	0 (0.13)	0.72 (0.43)	-0.41 (0.25)	0.12 (0.14)	0.12 (0.15)
E2	0.02 (0.39)	1.17 (0.75)	-0.36 (0.56)	No Data	0.32 (0.27)	0 (0.59)	0.73 (0.28)	0.44 (0.24)	0.42 (0.23)
G1	-0.41 (0.58)	-0.89 (0.77)	-0.51 (0.49)	No Data	-0.16 (0.49)	-0.3 (0.78)	0 (0.31)	-0.14 (0.49)	-0.17 (0.56)
D	-0.36 (0.43)	-1.15 (0.72)	-0.43 (0.7)	No Data	-0.33 (0.13)	-0.6 (0.56)	0.07 (0.2)	0 (0.13)	0.03 (0.12)
I	-0.92 (0.28)	-0.86 (0.45)	-0.36 (0.34)	No Data	-0.44 (0.13)	-0.66 (0.37)	0.04 (0.16)	-0.06 (0.12)	0 (0.12)

Transfer to colder Transfer to warmer Poor performance Good performance

b) Mean growing season precipitation (mm)

Test sites	Difference in MSP (mm) from source to site climate								
	H	G2	E1	E	E2	D1	G1	D	I
H	-14	-38	-60	-78	-79	-106	-98	-177	-184
G2	24	0	-22	-40	-41	-68	-60	-139	-146
E1	44	20	-2	-20	-21	-48	-40	-119	-126
E	53	29	7	-11	-12	-39	-31	-110	-117
E2	75	51	29	11	10	-17	-9	-88	-95
D1	80	56	34	16	15	-12	-4	-83	-90
G1	102	78	56	38	37	10	18	-61	-68
D	170	146	124	106	105	78	86	7	0
I	170	146	124	106	105	78	86	7	0

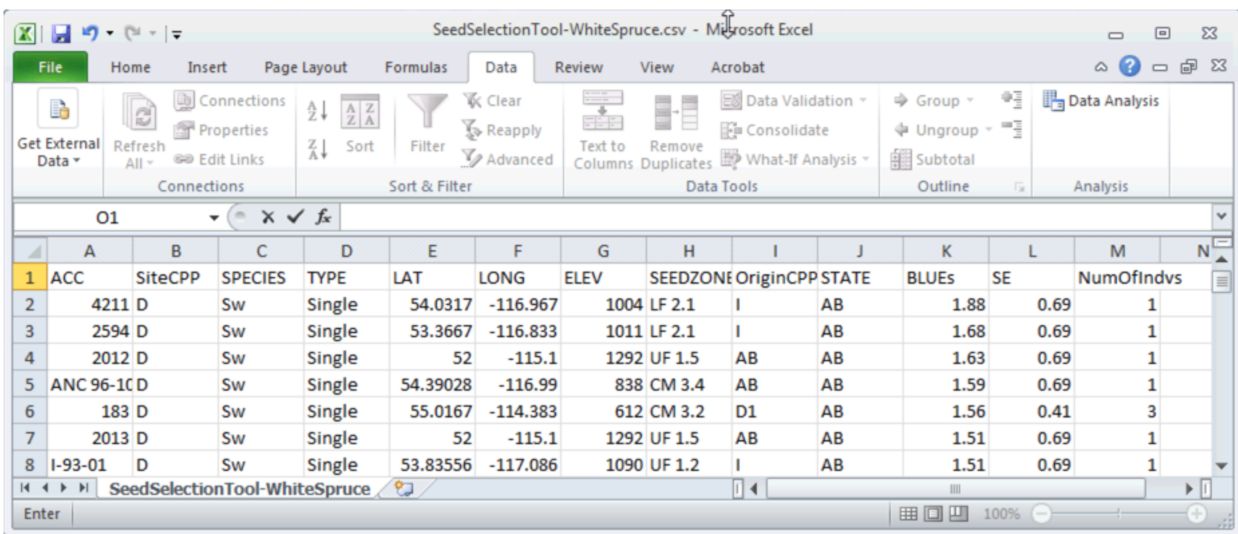
Test sites	Performance of transferred sources relative to local								
	H	G2	E1	E	E2	D1	G1	D	I
H	0 (0.3)	-0.49 (0.31)	0.69 (0.37)	0.81 (0.41)	-0.4 (0.78)	0.02 (0.31)	-1.13 (0.32)	-0.54 (0.49)	-0.42 (0.56)
G2	-0.47 (0.21)	0 (0.18)	0.55 (0.28)	0.51 (0.33)	-0.24 (0.57)	0.17 (0.2)	-0.12 (0.2)	-0.12 (0.35)	-0.01 (0.43)
E1	-0.93 (0.38)	-0.55 (0.54)	0 (0.29)	-0.22 (0.23)	0.28 (0.32)	-0.6 (0.26)	-0.57 (0.71)	-0.62 (0.39)	-0.38 (0.51)
E	-0.82 (0.32)	-0.47 (0.46)	-0.01 (0.24)	0 (0.21)	0.18 (0.26)	-0.29 (0.2)	-0.89 (0.4)	-0.47 (0.21)	-0.49 (0.22)
E2	0.02 (0.39)	-0.36 (0.56)	1.17 (0.75)	No Data	0 (0.59)	0.32 (0.27)	0.73 (0.28)	0.44 (0.24)	0.42 (0.23)
D1	-0.38 (0.18)	-0.78 (0.2)	0.21 (0.29)	0.52 (0.33)	0.72 (0.43)	0 (0.13)	-0.41 (0.25)	0.12 (0.14)	0.12 (0.15)
G1	-0.41 (0.58)	-0.51 (0.49)	-0.89 (0.77)	No Data	-0.3 (0.78)	-0.16 (0.49)	0 (0.31)	-0.14 (0.49)	-0.17 (0.56)
D	-0.36 (0.43)	-0.43 (0.7)	-1.15 (0.72)	No Data	-0.6 (0.56)	-0.33 (0.13)	0.07 (0.2)	0 (0.13)	0.03 (0.12)
I	-0.92 (0.28)	-0.36 (0.34)	-0.86 (0.45)	No Data	-0.66 (0.37)	-0.44 (0.13)	0.04 (0.16)	-0.06 (0.12)	0 (0.12)

Transfer to drier Transfer to wetter Poor performance Good performance

Figure 4. Matrices of the change in (a) mean annual temperature and (b) growing season precipitation compared to estimated relative performance presented in Table 2 and Figure 3. Coloured cells represent when three or more parents were used to estimate the relative performance of the CPP region.

While a measure of relative performance under transfers between regions provides a general framework to help guide seed-transfer decisions among Alberta's white spruce CPP regions, seed selection for planting should be based on the performance of individual populations within the CPP regions. Therefore, as a second step, the relative performance of parents in trial experiments was analyzed with a mixed model with the parent accession identification number, test site CPP region, and their interaction as fixed effects, using the ASREML software implemented with the R programming language. Similar to the general transfers, the performance estimates for each parent were adjusted by subtracting the general performance of local material with each respective CPP region. The resulting best linear unbiased estimates provide a measure of parent performance compared to local parents within the CPP region, with positive values indicating better-than-average performance. Further, the standard error provides a measure of range of performance, with smaller values indicating that a parent performed similarly in all experimental trials within the CPP region.

Performance estimates for all parents within tested CPP regions are provided in an interactive Excel-format Searchable Database for white spruce supplementary to this report (Figure 5). This tool can be queried using simple filtering and sorting functions either to select the top-performing parents for planting a site within a specific CPP region, or to identify where a specific parent should be planted to achieve good performance. Further, queries can be made to investigate how a particular parent performed when transferred to a novel climate that represents projected climate change aiding the development of guidelines for both seed transfer under climate change and orchard rogueing.



ACC	SiteCPP	SPECIES	TYPE	LAT	LONG	ELEV	SEEDZONE	OriginCPP	STATE	BLUEs	SE	NumOfIndvs
4211	D	Sw	Single	54.0317	-116.967	1004	LF 2.1	I	AB	1.88	0.69	1
2594	D	Sw	Single	53.3667	-116.833	1011	LF 2.1	I	AB	1.68	0.69	1
2012	D	Sw	Single	52	-115.1	1292	UF 1.5	AB	AB	1.63	0.69	1
ANC 96-1C	D	Sw	Single	54.39028	-116.99	838	CM 3.4	AB	AB	1.59	0.69	1
183	D	Sw	Single	55.0167	-114.383	612	CM 3.2	D1	AB	1.56	0.41	3
2013	D	Sw	Single	52	-115.1	1292	UF 1.5	AB	AB	1.51	0.69	1
I-93-01	D	Sw	Single	53.83556	-117.086	1090	UF 1.2	I	AB	1.51	0.69	1

Figure 5. Example of the Excel-format white spruce Searchable Database that is available as a supplement to this report. This tool can be queried using simple filtering and sorting functions either to select the top-performing parents for planting a site within a specific CPP region, or to identify where a specific parent should be planted to achieve good performance. For example, here the table has been sorted by the column SiteCPP and by the relevant performance estimate (BLUEs) for all parents tested in CPP region D, with the top performers at the top of the list.

Results 2: Synthesized Results for Lodgepole Pine

The lodgepole pine analyses were conducted using the same methodology as the previously described white spruce project. Below, details for the lodgepole pine results are reported. For further details on the analysis methodology, refer to the previous white spruce analyses.

2.1 Summary of Genetic Information and Seed Transfer

The lodgepole pine Controlled Parentage Program is the second-largest in the province, encompassing a total area of approximately 77,941 square kilometres dominated by mixedwood forest types (Figure 6). This area is divided into six individual regions identified as CPP regions A, B1, B2, C, J, and K; however, there are boundary overlaps between the regions located in the Alberta foothills: A, B1, B2, C, and K1. In Figure 6, different colours identify the regions, with the overlaps illustrated by the outlines in the region's corresponding colour. Given that there are no improvement programs for the overlap regions themselves, for this project experimental site locations and collection origins that fall within an overlap between regions are used to establish seed-transfer guidelines for multiple regions.

Table 3 outlines the 16 progeny and provenance trial series that were evaluated in this project. In total, 141,199 individual trees tested within 42 individual experiments at 29 geographic locations were evaluated (Figure 6, Table 3). For each test installation, recorded locations were extracted from establishment reports provided by Alberta Environment and Sustainable Resource Development (ESRD). The recorded values were confirmed against satellite imagery that showed the planting sites (Google Earth), and elevation values were then cross-checked against digital elevation models at both 25- and 250-metre resolution. Discrepancies were resolved though consultation with Leonard Barnhardt (ESRD), who has personal knowledge of all of the planting sites.

Trial Series	Year Planted	Number of Sites	Number of Parents	Evaluation Year
Progeny test series				
G127	1981	4	404	27
G128	1982	4	232	30
G154	1991	2	466	20
G160	1994	2	52	15
G293	1996	2	115	14
G329	1998	3	169	15
G346	2000	3	117	9
G356	2002	3	250	14
G358	2003	4	32	10
G800	1978	2	160	22
Provenance test series				
G134	1985	8	24	25
G289	1992	1	169	20
Berland 3	1981	1	14	15
Berland 5	1980	1	14	16
Embarrass	1980	1	14	16
Marlboro	1979	1	17	16

Table 3. Summary of lodgepole pine progeny and provenance trials.

The breakdown of origin for the parents tested within each CPP region is illustrated in Figure 6, with the size of the transfer circles proportionally reflecting the number of transfers across all CPP regions. The number of seed transfers among the CPP regions varies between 0 and 462 unique parents, with higher numbers of parents tested within a CPP region often originating from adjacent CPP regions. Transfers of seed beyond CPP regions adjacent to the region of origin are limited, mostly reflecting less than 10 unique parents. For example, material originating in CPP region B1 has been widely distributed in its neighbouring regions, but few parents are transferred to the most northern (J) and southern (K1) CPP regions (Figure 6).

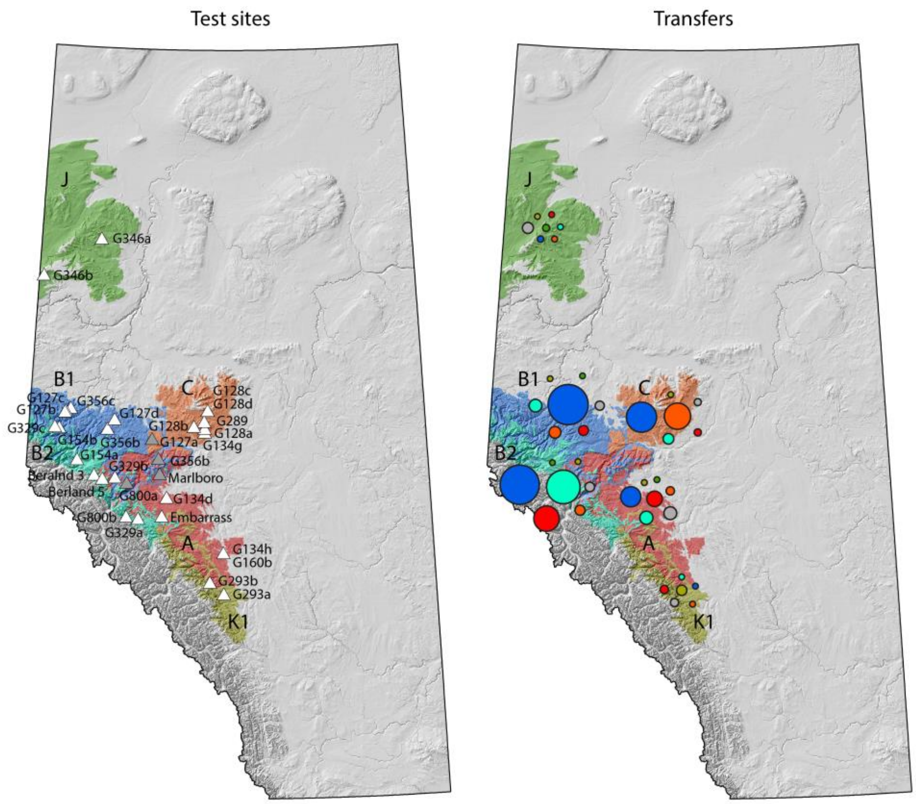


Figure 6. Delineations and transfers among Alberta's lodgepole pine CPP regions. For regions that overlap (A, B1, B2, C, and K1), the overlap boundaries are defined by the region outline of the same colour. Test sites that fall within each region are presented as Δ, with test sites that occur in an overlap between adjacent CPP regions coloured grey. For each site, the trial series tested are identified with the trial series test number (e.g., G127a). For the map of transfers, the size of the circles proportionally reflects the number of unique parents originating from within each coloured CPP region, respectively.

2.2 Climatic Summary of the Lodgepole Pine CPP Regions

The climatology of Alberta's lodgepole pine CPP regions is related to their proximity within Alberta's natural regions and sub-regions, and primarily driven by a latitudinal temperature gradient, and precipitation patterns that are related to regional topography.

The range of mean annual temperature and mean annual precipitation for each lodgepole pine CPP region at one-kilometre resolution, along with the climate for each test site that falls within the region, are illustrated in Figure 7. Test sites that occur in overlapping CPP regions are represented by a grey triangle corresponding to Figure 6. CPP region J (dark green) is unique in the lodgepole pine program as it is located in significantly further northern latitude in the boreal forest compared to the Rocky Mountain Foothills, where the remaining regions occur (Figure 6). This region experiences the coldest and driest climate of all the lodgepole pine regions, with mean annual temperature ranging between –2 and 1°C, and mean annual precipitation ranging between 400 and 550 mm (Figure 7). The remaining CPP regions located in the Rocky Mountain Foothills all experience similar warm and wet climatic ranges characteristic of the area. In these regions, mean annual temperatures range between 1 and 3°C, and mean annual precipitation ranges between 550 and 800 mm (Figure 7). However, the mean annual precipitation in CPP region B2 (cyan) is observed to be up to 1,000 mm as a result of the high elevations (up to 1,650 metres) that occur within the region.

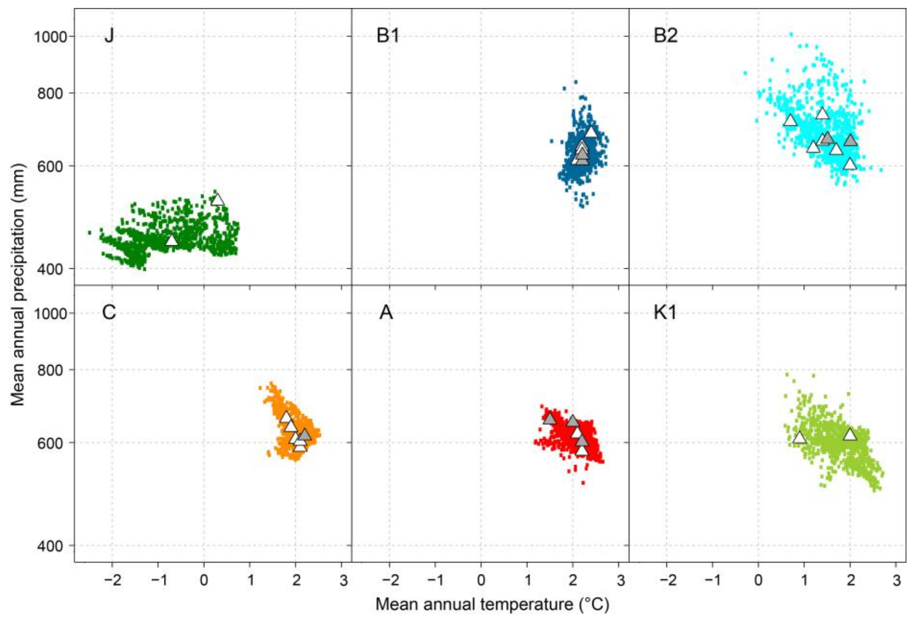


Figure 7. Summary of the mean annual precipitation over the mean annual temperature for each of Alberta's lodgepole pine CPP regions. Coloured points represent the range of climate at one-kilometre resolution for each region. The climates of each of the test sites are also provided as Δ. Test sites that occur in an overlap between adjacent CPP regions are coloured grey.

For most CPP regions, performance of material in experimental tests can aptly be extended to the region as a whole, as test sites' climates are a good representation of the climatic range of the region. Note that this project only includes a subset of all experimental test sites within each region where data was available. Recently established sites with young trees that could potentially fill the climate gaps would therefore not be included in this project or in Figure 7. In the future, additional data could revise results from this project.

2.3 Estimated Relative Performance of Seed Material under Transfer

Estimates of relative performance (i.e., standard deviations away from the local) for lodgepole pine material under transfer, including the standard error of the estimates, is presented in Table 4. Values along the diagonal representing local transfers are set to zero, and values under seed transfer indicate whether relocated seed performed worse (negative) or better (positive) than the local stock. Relative performance of transferred material is further illustrated in Figure 8, where red and green arrows indicate worse- and better-performing material, respectively, and the width of the arrow indicates the magnitude of performance. Further, Figure 9 presents the shifts in both the mean annual temperature (°C) and growing season precipitation (mm), compared to the estimated performance of seed material under transfer between the CPP regions (Table 4).

Interestingly, in almost all regions we found that local sources were the best performers (Table 4), suggesting that in most CPP regions seed is optimally adapted to its current environment. Local sources from CPP region B2, which represents a mild and wet high elevation (between 1,050 and 1,650 m) environment, were outperformed by seed originating from warmer lower-elevation regions (Table 4, Figures 7). Moreover, region B2 sources were always outperformed when transferred to warmer environments at lower elevations (Figure 9). Northern transfers of material originating from Rocky Mountain Foothills ecosystems into boreal ecosystems was found to be disadvantageous for all sources (Figure 9), likely resulting from parents experiencing at least a 2°C and 120 mm reduction in temperature and precipitation, respectively, when transferred (Figure 9). Within the Rocky Mountain Foothills ecosystems, southern

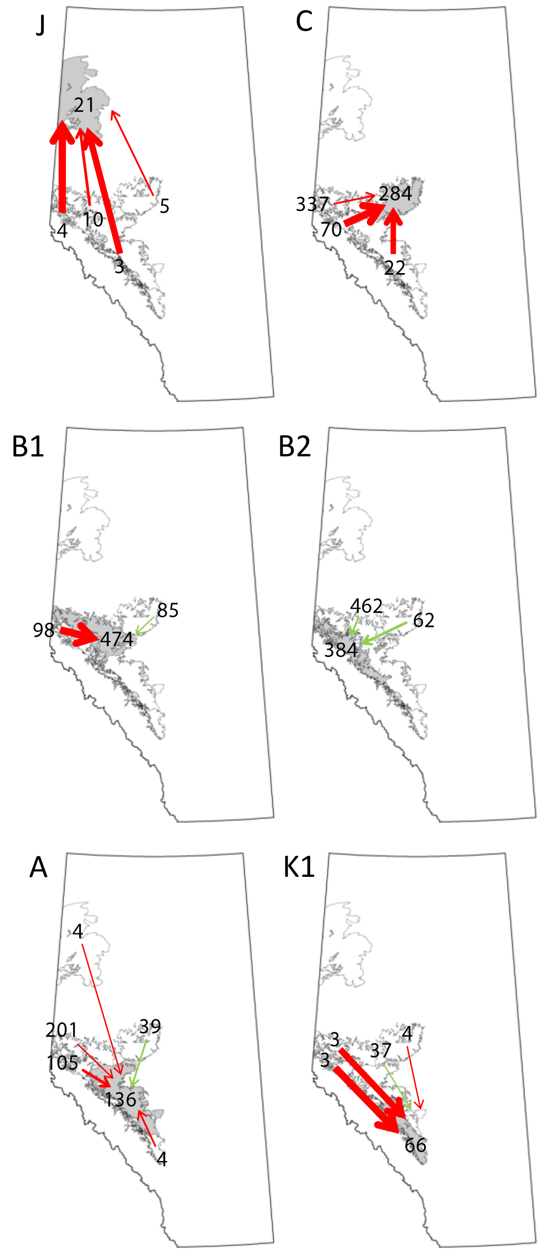


Figure 8. Illustration of the relative performance of CPP seed material when tested within the local and alternate regions, with red and green arrows representing below- and above-average performance compared to the local populations, respectively. The width of the arrows represents the magnitude of performance provided in Table 3. The number of unique parents the relative performance is calculated from is also provided.

transfers between adjacent regions appear to result in equal or slightly better performance than the local stock (e.g., from CPP region C to A, Figure 8). However, southern transfers over longer distances were found to be unfavourable (e.g., from CPP region B1 and B2 to K1, Figure 8).

Performance estimates for all parents within tested CPP regions are provided in an interactive Excel-format Searchable Database for lodgepole pine supplementary to this report (Figure 10). This tool can be queried using simple filtering and sorting functions to either select the top-performing parents for planting a site within a specific CPP region, or to identify where a specific parent should be planted to achieve good performance. Further, queries can be made to investigate how a particular parent performed when transferred to a novel climate that represents projected climate change aiding the development of guidelines for both seed transfer under climate change and orchard rogueing.

To\From	A	B1	B2	C	J	K1
A	0 (0.09)	-0.02 (0.08)	-0.44 (0.1)	0.2 (0.13)	-0.03 (0.45)	-0.18 (0.38)
B1	-0.23 (0.09)	0 (0.06)	-1.1 (0.08)	0.06 (0.08)	-0.51 (0.46)	-1.03 (0.45)
B2	0.32 (0.07)	0.21 (0.07)	0 (0.07)	0.39 (0.1)	-0.37 (0.59)	0.5 (0.58)
C	-0.78 (0.16)	-0.25 (0.07)	-1.25 (0.11)	0 (0.08)	No data	-0.43 (0.6)
J	-0.84 (0.34)	-0.44 (0.22)	-1.33 (0.33)	-0.25 (0.28)	0 (0.21)	-1.1 (0.46)
K1	0.01 (0.17)	-0.93 (0.33)	-1.38 (0.35)	-0.05 (0.3)	No data	0 (0.16)

Table 4. Best linear unbiased estimates indicating the relative performance of seed under transfer among Alberta's lodgepole CPP regions. Values indicate the number of standard deviations below (negative) or above (positive) the average performance of local material from the CPP region. The standard error for estimates is presented to provide a measure of uncertainty in performance estimates over seed material of a common origin CPP. Values that are calculated with less than three populations under transfer are greyed.

a) Mean annual temperature (°C)

Test sites	Difference in MAT (°C) from source to site climate					
	J	K1	B2	A	C	B1
J	-0.5	-2.6	-2.5	-2.9	-3	-3.2
K1	1.8	-0.3	-0.2	-0.6	-0.7	-0.9
B2	1.9	-0.2	-0.1	-0.5	-0.6	-0.8
A	2.4	0.3	0.4	0	-0.1	-0.3
C	2.5	0.4	0.5	0.1	0	-0.2
B1	2.6	0.5	0.6	0.2	0.1	-0.1

Transfer to colder

Transfer to warmer

Test sites	Performance of transferred sources relative to local					
	J	K1	B2	A	C	B1
J	0 (0.21)	-1.1 (0.46)	-1.33 (0.33)	-0.84 (0.34)	-0.25 (0.28)	-0.44 (0.22)
K1	No Data	0 (0.16)	-1.38 (0.35)	0.01 (0.17)	-0.05 (0.3)	-0.93 (0.33)
B2	-0.37 (0.59)	0.5 (0.58)	0 (0.07)	0.32 (0.07)	0.39 (0.1)	0.21 (0.07)
A	-0.03 (0.45)	-0.18 (0.38)	-0.44 (0.1)	0 (0.09)	0.2 (0.13)	-0.02 (0.08)
C	No Data	-0.43 (0.6)	-1.25 (0.11)	-0.78 (0.16)	0 (0.08)	-0.25 (0.07)
B1	-0.51 (0.46)	-1.03 (0.45)	-1.1 (0.08)	-0.23 (0.09)	0.06 (0.08)	0 (0.06)

Poor performance

Good performance

b) Mean growing season precipitation (mm)

Test sites	Difference in MSP (mm) from source to site climate					
	J	K1	B1	A	B2	C
J	1	-127	-132	-143	-147	-162
K1	136	8	3	-8	-12	-27
B1	143	15	10	-1	-5	-20
A	144	16	11	0	-4	-19
B2	146	18	13	2	-2	-17
C	157	29	24	13	9	-6

Transfer to drier

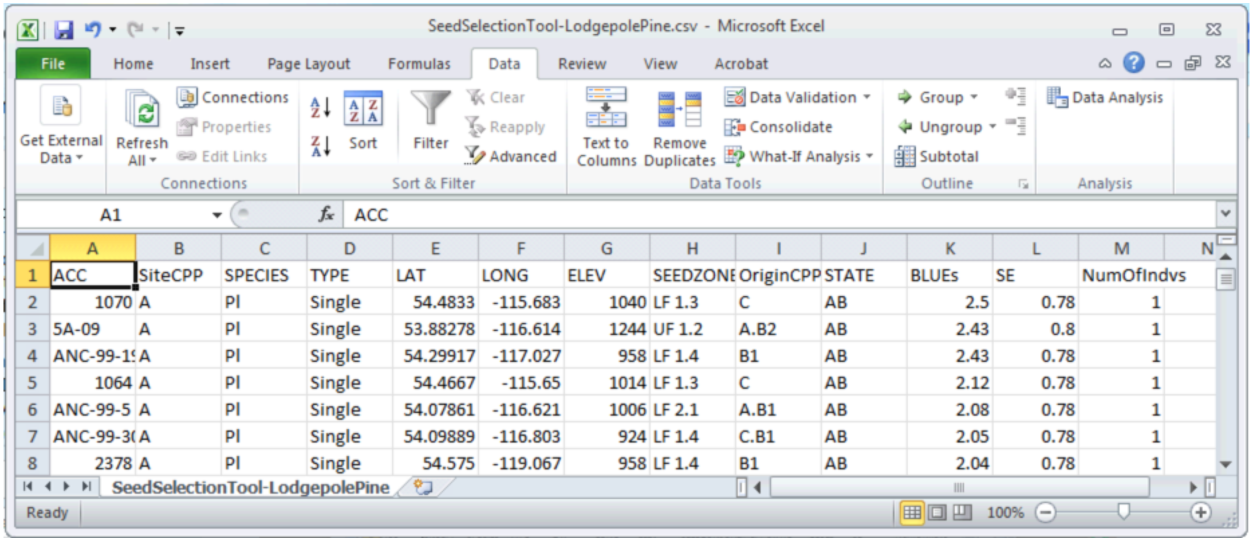
Transfer to wetter

Test sites	Performance of transferred sources relative to local					
	J	K1	B1	A	B2	C
J	0 (0.21)	-1.1 (0.46)	-0.44 (0.22)	-0.84 (0.34)	-1.33 (0.33)	-0.25 (0.28)
K1	No Data	0 (0.16)	-0.93 (0.33)	0.01 (0.17)	-1.38 (0.35)	-0.05 (0.3)
B1	-0.51 (0.46)	-1.03 (0.45)	0 (0.06)	-0.23 (0.09)	-1.1 (0.08)	0.06 (0.08)
A	-0.03 (0.45)	-0.18 (0.38)	-0.02 (0.08)	0 (0.09)	-0.44 (0.1)	0.2 (0.13)
B2	-0.37 (0.59)	0.5 (0.58)	0.21 (0.07)	0.32 (0.07)	0 (0.07)	0.39 (0.1)
C	No Data	-0.43 (0.6)	-0.25 (0.07)	-0.78 (0.16)	-1.25 (0.11)	0 (0.08)

Poor performance

Good performance

Figure 9. Matrices of the change in mean annual temperature and growing season precipitation compared to estimated relative performance presented in Table 4 and Figure 8. Coloured cells represent when three or more parents were used to estimate the relative performance of the CPP region.



ACC	SiteCPP	SPECIES	TYPE	LAT	LONG	ELEV	SEEDZONE	OriginCPP	STATE	BLUEs	SE	NumOfIndvs
1070	A	Pl	Single	54.4833	-115.683	1040	LF 1.3	C	AB	2.5	0.78	1
5A-09	A	Pl	Single	53.88278	-116.614	1244	UF 1.2	A.B2	AB	2.43	0.8	1
ANC-99-1!	A	Pl	Single	54.29917	-117.027	958	LF 1.4	B1	AB	2.43	0.78	1
1064	A	Pl	Single	54.4667	-115.65	1014	LF 1.3	C	AB	2.12	0.78	1
ANC-99-5	A	Pl	Single	54.07861	-116.621	1006	LF 2.1	A.B1	AB	2.08	0.78	1
ANC-99-3(	A	Pl	Single	54.09889	-116.803	924	LF 1.4	C.B1	AB	2.05	0.78	1
2378	A	Pl	Single	54.575	-119.067	958	LF 1.4	B1	AB	2.04	0.78	1

Figure 10. Example of the Excel-format lodgepole pine Searchable Database, which is available as a supplement to this report. This tool can be queried using simple filtering and sorting functions to either select the top-performing parents for planting a site within a specific CPP region, or to identify where a specific parent should be planted to achieve good performance. For example, here the table has been sorted by the column SiteCPP and by the relevant performance estimate (BLUEs) for all parents tested in CPP region A, with the top performers at the top of the list.

3.0 Major Conclusions and Recommendations

As stated earlier, for most of the CPP regions, the local populations appear to be the best choice, at least in the near future. Nevertheless, opportunities exist for moving seed among neighbouring sections of some of the CPP regions. In the boreal forest region, moving seed from south to north and from lower to higher elevations in mountainous regions may be feasible. While a movement of seed from central Alberta (southern boreal) to northern Alberta (northern boreal) to increase forest productivity is theoretically desirable, northern Alberta is predicted to be much drier than central Alberta. Therefore, a targeted testing for drought tolerance to clearly identify genotypes that combine both the high growth potential characteristic of southern boreal populations and the drought tolerance needed for reforestation in the drier north is needed. It is expected that field-testing on sites developed under the CCEMC project will address this. In the interim, Alberta should seek to integrate results from this project with those in British Columbia and elsewhere where some of the populations and parent trees used in the CCEMC study have been tested for drought tolerance in the greenhouse.

Summaries from climate change modelling and genetic analysis for individual CPP programs have been developed and will be made available to CPP owners (proponents).

4.0 Acknowledgements

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