# Growth and survival of Siberian larch in Alberta at the species, population and family level

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Growth and survival of Siberian larch in Alberta at the species, population and family level

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Abstract

Survival and growth of Siberian larch (SL, *Larix sibirica* Ledeb.) were compared to three conifer species native to Alberta, Canada: lodgepole pine (LP; *Pinus contorta* var. *latifolia* Engelm.), white spruce (WS, *Picea glauca* (Moench) Voss) and jack pine (JP, *Pinus banksiana*, Lamb.) at 12, 10 and three trial locations, respectively. The average data age was 18 years (range: three to 27). Survival of SL averaged 4.2% and 6.5% worse than LP and WS, respectively, while it was 5% better than JP. SL grew 25%, 94% and 23% taller than LP, WS and JP, respectively. Stem forking rates were similar between LS and LP, WS and JP. The best seed sources for Alberta were mature trees established in Alberta and Saskatchewan but whose initial provenances are unknown. The Russian Altai Mountain source grew well at high elevations while the Finnish Raivola performed well in the northern, low elevation area. Open-pollinated progeny tests of 58 families planted in five diverse locations yielded individual tree narrow-sense heritabilities and family mean heritabilities for height at age 15 of 0.15 and 0.59, respectively. The type B between-site genetic correlation was 0.44 indicating a strong genotype × environment interaction. SL has performed well in Alberta and its growth can be further improved by selection and breeding from appropriate seed sources.

Keywords: Siberian larch, exotic species, growth, genetic variance, provenance
Introduction

Larch forests represent 36% of Russia’s forested areas (FAO 2012) and 34% of its total timber volume (Milyutin and Vishnevetskaia, 1995). The main species include SL and Gmelin larch (L. gmelinii Rupr.). In contrast, in Canada larch represents only 0.6% of total timber volume (CNFI 2018) even though the most common larch species in Canada, tamarack (L. laricina (DuRoi) K. Koch), has one of the widest distributions among conifers in North America (Johnston 1990).

Tamarack and the other two native North American larches, western larch (L. occidentalis Nutt.) and subalpine larch (L. lyallii Parl.) occur in Alberta. While they are important components of local ecosystems, none of them are of commercial value in the province.

The natural range of SL extends from 36 to 113°E, 47 to 71°N, and from 10 to 2400 m (Sokolov et al. 1977; IAEARNC 2009; Farjon 2013). SL growing in the north-east European part of Russia, in the Ural and in West Siberia by the Ob and Irtish Rivers is sometimes considered a separate species L. sukaczewii (Abaimov et al. 1998). In this article we treat it as a variety of SL (L. sibirica var. sukaczewii, sensu Farjon (1990) and Milyutin and Vishnevetskaia (1995)). SL wide distribution covers locations with climatic conditions similar to Canadian prairie provinces.

SL has been used as an exotic species in reforestation because of its fast juvenile growth, potential for high fibre yield, tolerance to low temperatures, tolerance of low intensity fires, and high strength decay-resistant wood (Hakkila and Winter 1974; Martinsson 1995; Milyutin and Vishnevetskaia 1995; Redko and Mälkönen 2005; Wirth 2005; Ruotsalainen 2017). Shelterbelt use of SL in dry environments of southern Saskatchewan and North Dakota suggests that this species also has good drought tolerance (Carr et al. 2004). It is the most important non-native forest tree species in Finland (Ruotsalainen 2017). It has also been planted as a timber species in
Sweden (Karlman et al. 2011), Estonia (Sander and Meikar 2009) and Iceland (Blöndal and Snoranson 1995). In northern Alaska, SL along with LP are the most commonly planted exotic conifers (Alden 2006). SL was introduced to Alberta and other Canadian prairie provinces first in the early 1900’s for use in small private woodlots, shelterbelts and as an ornamental plant (Rehfeldt et al. 1999; Carr et al. 2004). It has not been used for commercial reforestation in Alberta.

In Alberta the main commercial conifer species are LP and WS. They have wide distributions across the province (Figure 1) and these two species account more or less equally for almost all reforestation planting in Alberta. JP is an important commercial species in north-eastern Alberta.

SL has been planted in Alberta in a number of field tests that include species, seed source, open pollinated progeny and demonstration trials. The tests were planted starting in 1980 and have been periodically measured. The data from all tests were compiled and analysed in order to: (i) compare field performance of SL to the performance of the main coniferous commercial species (LP, WS and JP), (ii) evaluate differences among the SL seed sources and (iii) evaluate genetic variation of SL.

Materials and methods

Siberian larch field trials in Alberta

A total of 24 SL trials were planted from 1980 to 1998 in 15 climatically diverse locations in Alberta (Table 1, Figure 1), with 1 to 4 trials at each location. Almost all trials were randomized complete block designs with row plots (Table 1). They were planted at 2.5 x 2.5 m spacing after mechanical site preparation and periodically weeded to minimize competing vegetation every three to five years if needed. Survival, height (HT), diameter at breast height (DBH), and stem
forking were measured and scored periodically. Measurement age averaged 20 years (range:
three to 30). A tree was considered forked if it had more than one leader extending for at least
two internodes from the fork base assuming each internode represented one year of height
growth. SL seedlots included provenance collections, Canadian bulk collections of unknown
origin, and open pollinated family collections.

_Siberian larch species trials_

Comparison of SL performance to that of Alberta main commercial conifer species was done
separately for each trial location. Where more than one trial was planted in a location, the
location results were averaged across all available comparisons. Differences between the species
in locations where more than one trial was planted were called statistically significant ($\alpha = 0.05$)
if at least one trial showed statistically significant differences. Where the same trial was
measured over several years, the oldest data were used for comparisons. Not all experiments had
both SL and the commercial species planted as part of the same test: seven tests planted in seven
locations included LP and WS and one test included JP. The baselines for the remaining tests
were LP, WS and JP trees planted in adjacent tests in the same experimental location. These tests
were planted at the same density following the same site preparation and maintenance as the SL
experiments.

The commercial species trials typically included seed sources from many locations. SL was
compared with the mean performance of all “local” provenances. Based on previous studies
(Rweyongeza et al. 2007, 2010), a control local population of a native species was defined as a
population originating from within 1° north to 2° south, 2° east or west, and +300 m to -100 m of
the test site elevation. When a local provenance was not available (e.g., where the test was
outside the species’ range), the performance mean of all provenances was used as a baseline. The same data age was used for comparisons. In a few instances, the performance at the matching age was estimated by projecting a species’ performance at ± one year based on growth-age regressions. Because not all native species were planted in all SL test locations, or there were no data of suitable age for comparisons, the differences in performance could not be evaluated for all 15 locations with SL tests. The number of locations allowing comparison with LP, WS and JP were 12, 10 and three, respectively. A total of 6984, 4865 and 1285 SL trees were planted in tests allowing for performance comparisons with LP, WS and JP, respectively.

Two-way ANOVA’s with species and block effects and F-tests were used to evaluate the significance of differences (α=0.05) in height and diameter between species in the same test. Survival was analysed using logistic regression and chi-square statistics. For comparisons where SL and the commercial species were planted in the same location but in different tests, significance of differences in height and diameter was evaluated using two-tailed t-tests with equal or unequal variance, and survival differences were assessed using chi-square or Fisher’s exact tests, depending on sample size (SAS Institute 2012).

Siberian larch seed source trials

A total of 17 SL seed sources have been planted in Alberta in various tests (Table 2). These sources include 11 seed collections from Estonia, Finland and four Russian regions (Central, Volga, southern Siberia and south-central Siberia). The collections cover a range of 9.4° in latitude and 69.4° in longitude. By far the most planted source of SL in Alberta is the “Raivola” seed source originating from a commercial seed orchard in Finland planted with material from Raivola. Raivola is a forest established near St. Petersburg in 1738 with seed from Archangelsk
and Ural that is famous for its exceptional stem quality and growth (Redko 1995). Like the Raivola, the collections from Estonia are outside the species’ natural range. Six collections were from mature trees in Alberta, Saskatchewan and Manitoba (Table 2) of unknown origin.

Data from all tests planted in Alberta with more than one geographic seed source were included in analyses. Seven replicated test series, planted in 13 locations, included two to 14 seed sources per test (Table 1, excluding Grande Prairie and Calling Lake). Height data ranged from three to 30 years (average 20 years) and DBH data ranged from 13 to 30 (average 21 years). It was possible to compare the performance of seed sources across sites and ages as all trials included the Raivola source. The mean performance of each seed source (survival and growth) was calculated for each trial location and then expressed as a percent relative to the Raivola means.

**Siberian larch progeny trials**

An open-pollinated progeny test series was planted in 1996 at five locations in Alberta using seed collections from 58 trees from the Altai Mountains in South Central Siberia from 600 to 1650 m elevation. The locations include Smoky Lake (1), Diamond Hills (1), Clearwater, Dry Creek, and Whitecourt Mountain (2) (Table 1). Data on HT and DBH were collected at age 15, and analyzed using the following model:

\[
Y_{ijk} = \mu + S_i + R(S)_{ij} + F_k + FS_{ki} + e_{ijk}
\]

where:

- \(y_{ijk}\) is an individual of the \(kth\) family in the \(jth\) replication of the \(ith\) site (location);
- \(\mu\) is an overall mean;
- \(S_i\) is the fixed effect of the \(ith\) site;
- \(R(S)_{ij}\) is the fixed effect of the \(jth\) replication within the \(ith\) site;
$F_k$ is the random effect of $kth$ family $\sim$ IID $(0, \sigma^2_f)$;

$FS_{ik}$ is the random effect of $ith$ site by $kth$ family interaction $\sim$ IID $(0, \sigma^2_{sf})$;

$e_{ijk}$ is the random residual $\sim$ IID $(0, \sigma^2_e)$

The significance of family variance was evaluated with the REML likelihood ratio test (Gilmour et al. 2009). The LogL value of the model with the family effect included were subtracted from the LogL value of the reduced model (i.e. one without the family effect). The significance was determined by comparing $2 \times \Delta\text{LogL}$ values with the critical value of the chi-square distribution at 1 df and $\alpha=0.05$. To evaluate the potential of selection, parental age 15 breeding values (BVs) were calculated as Best Linear Unbiased Predictions. BVs were expressed as percent gain with respect to the mean performance of all families.

The following formulae were used to calculate individual tree ($h^2_i$) and family mean ($h^2_f$) heritabilities:

\begin{equation}
(2) \quad h^2_i = \frac{4 \sigma^2_f}{\sigma^2_e + \sigma^2_f + \sigma^2_{sf}}
\end{equation}

\begin{equation}
(3) \quad h^2_f = \frac{\sigma^2_f}{\frac{\sigma^2_e}{nrs} + \frac{\sigma^2_{sf}}{s} + \sigma^2_f}
\end{equation}

Where $\sigma^2_e =$ error variance; $\sigma^2_f =$ family variance; $\sigma^2_{sf} =$ site $\times$ family variance; $n =$ number of trees per family per replication; $r =$ number of replicates per site; $s =$ number of sites.
The magnitude of the genotype by environment interaction was evaluated using the between-site type B genetic correlation \((r_b)\) calculated as follows (Yamada 1962):

\[
(4) \, r_b = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_{sf}^2}
\]

Results

Species variation and performance

Survival of SL was on average 4.2% lower than that of LP and it ranged by location from -26% to 14% (Figure 2). Survival rates were significantly different \((p\leq0.05)\) between the species in all locations except for Diamond Hills, Grande Prairie and Virginia Hills. SL outperformed LP in HT and DBH growth by 25% at the average test age 18 and 15% at the average test age 19, respectively (Figure 2). The differences between the species in HT and DBH were statistically significant \((p\leq0.05)\) in all locations except for DBH in Mitsue South. The Smoky Lake results are not presented and were not included in the overall mean calculation because LP had anomalously high mortality and poor growth there. The only site where LP outperformed SL is Clearwater, a high elevation, low productivity site. In Gurtler SL outperformed LP by a much greater margin than at other sites, but the comparison is based on a very young age of three. Across all eight locations where LP local seedlots were planted, SL grew taller than LP by 23%. Forking rates were comparable between the two species, averaging 15%, and 13% for SL and LP, respectively.

Across all 10 comparison locations, the survival of SL was on average lower than that of WS by 6.5% and it ranged by location from -32% to 21%, (Figure 3). Survival rates were statistically
different in all locations except for Smoky Lake and Virginia Hills. SL grew better than WS in HT at the average test age 18 and in DBH at the average test age 21 by 94% and 79%, respectively (Figure 3), and was superior in all 10 locations. Differences between the species in HT and DBH were statistically significant (p≤0.05) in all locations. In contrast to the LP results, SL growth rates were much higher than WS not only at the very young (Gurtler) but also at older ages (e.g., age 27 in Calling Lake). Forking rates were comparable between the two species with the average forking rates for SL and WS at 17%, and 22%, respectively.

Across all three comparison locations, the survival of SL was on average higher than that of JP by 5% (range: -5% to 22%, Figure 4). Survival rates were statistically different in all locations except for Grande Prairie. SL on average outperformed JP by 23% and 22% for HT and DBH growth, respectively, at the average age 20. Differences between the species in HT and DBH were statistically significant (p≤0.05) in all three locations. Forking rates averaged across the tests were 9% for both species.

*Siberian larch seed source variation and performance*

There were large differences among the seed sources within and among the sites in survival (Table 3), HT (Figure 5) and DBH (details not presented). For example, at Hay River, survival among 11 seed sources ranged from 6% to 68%. In terms of height growth, sources from Estonia performed the best (Kambja) and the worst (Tartu) on that site. Indian Head, the second most frequently tested seed source in Alberta (present in 9 sites), exhibited considerable performance differences among sites. Its survival ranged from 51% at Hay River to 93% at Wandering River (Table 3), while HT growth relative to Raivola ranged from -8% at Hay River to 54% at Swartz Creek.
Growth of the seed sources differentiated along the elevation and latitude of the test sites since elevation of the sites generally decrease with increasing latitude. Growth of the Raivola source compared to that of other seed sources decreased with increasing test site elevation (Figure 5). At higher elevations (above 1,250 m), the best seed sources were Beaverlodge and Altai Mountains (Figure 5). At medium elevations (600-1,250 m), the best source was Indian Head followed by several sources including Edmonton, Ivanovo Oblast, Krasnoyarsky Krai and Oliver Tree Nursery. At elevations below 600 m Raivola performed well (particularly at the highest latitude), followed by Indian Head. The Altai Mountain population performance changed within a relatively short elevational difference at the highest elevations. This source performed exceptionally well at 1,287 m at Clearwater but grew less than Raivola at 998 m at Diamond Hills. Both sites are in Lower Foothills Natural Subregion, implying topographic, climatic, and floristic similarity (Natural Regions Committee 2006).

*Siberian larch family variation and performance*

There were large differences between the sites in HT genetic parameters (Table 4). Family variance was not significantly different from zero in Dry Creek. The other four sites were found informative but differed in quality. The Individual tree heritability was overestimated in Diamond Hills and was moderate to high in the other three sites. Across all sites the individual tree heritability and family mean heritabilities were moderate at 0.15 and 0.59, respectively (Table 4). Large genotype by environment interaction was evident as indicated by the type B genetic correlations of 0.44. Similar results to those for HT were found for DBH based on individual site data and in the combined analysis (details not presented). In the combined DBH analysis the individual tree narrow sense heritability was 0.16, family mean heritabilities 0.62
and type B genetic correlations 0.53. Age 15 parental breeding values ranged from -23% to 11% for HT and -36% to 14% for DBH with respect to the population mean.

**Discussion**

*Species variation and performance*

SL showed superior growth performance across Alberta when compared to the commercially most important native conifers. While its survival rate was slightly below that of LP and WS, its height and diameter exceeded that of LP by 25% and 15%, respectively, and that of WS by 94% and 79%, respectively. Based on three tests, its performance was also superior to that of JP. SL was only shorter than any commercial species at one high elevation, low productivity site (Clearwater) where the local LP sources grew better.

LP and SL share many characteristics: both are early seral species characterized by relatively fast early growth and low shade tolerance, colonizing following fire disturbance (Lotan and Critchfield 1990; Schulze et al. 2012). In contrast, WS is a later successional species exhibiting slower initial growth and greater shade tolerance. Thus, it is not surprising that SL outperformed WS by a much wider margin than it did LP within the experimental timeframe.

It is uncertain if the early fast growth of SL in Alberta will translate into its greater productivity and/or shorter optimum rotation age compared to those of native conifers. In general larches are characterized by rapid early growth and by achieving maximum mean annual increment earlier than many other conifers (Bergstedt and Lyck 2007). In Alberta the average age of comparison was approximately one quarter of rotation age for pine and one fifth for spruce. Many factors can influence short- and long-term species performance: soil nutrient content, moisture availability, seed source, planting density, competition, pests and diseases and climatic conditions. In general,
it seems that on better quality sites larch may outperform local species but not necessarily on more marginal sites. Martinsson (1995) looked at the performance of SL (var. sukaczewii) in 20 stands 34-89 year old in northern Sweden. SL outperformed Scots pine and Norway spruce by 23% in stem wood volume growth (range: -53 to 281%), with superiority increasing with site index. The projected gross volume for a 100-year rotation ranged from 500 m³·ha⁻¹ on medium sites to 1000 m³·ha⁻¹ on the most productive site. In another study in Sweden, 40-year-old SL (var. sukaczewii) produced more volume than Norway spruce and Scots pine, though the difference between larch and Scots pine was not statistically significant (Karlman et al. 2013). Redko and Mälkönen (2005) reported yields of over 1000 m³·ha⁻¹ in planted Raivola larch with mean annual increments reaching 7.2 m³·ha⁻¹·yr⁻¹, starting to decline only after 148-166 years. These very old larch plantations had yields greater than nearby stands of Scots pine and Norway spruce. Alden (2006) concluded that on productive upland Alaskan sites, WS is not likely to overcome the early fast growth of SL.

In Alberta, SL has an anecdotal tendency to fork. Quantitative comparison to LP, WS and JP growing at the same sites show that the frequency of forking is actually similar among these species. It is possible that forking is just easier to observe in SL, particularly in winter. However, it is also possible that while the frequency of forking may not be that different, the severity of it may be, if early age forks persist in SL but not in LP and WS. As loss of apical dominance can be due to e.g. low temperature, drought, insects, or mechanical damage, different factors may have contributed to the forking rates observed SL, LP, WS and JP.

Siberian larch seed source variation and performance
To maximize sample size and make the evaluation more conservative, we compared species based on the mean of all SL seed sources planted in a given test. However, there were large differences in growth performance among the seed sources used in Alberta indicating that there is a considerable potential to further improve performance of SL in the province. The best sources for Alberta were those collected from mature trees in Alberta (Beaverlodge) for higher elevations and from Saskatchewan (Indian Head) for medium and lower elevation. The Raivola collection was a very good source for low elevation/high latitudes and a slightly below average source for locations with medium elevations and/or medium latitudes. This seed source must be avoided in higher elevations. Large differences among SL provenances have been found in other studies (e.g. Karlman and Martinsson 2007; Lukkarinen et al. 2010; Karlman et al. 2011; Fedorkov 2014).

The superiority of Canadian sources may have resulted from their origin. It is also likely that the original plantings have gone through selection in situ that eliminated the less hardy and slow growing individuals. This effect combined with some mass phenotypic selection at the time of seed collection likely resulted in a certain level of improvement over the seed sources from Russia and Europe.

In British Columbia, LP outperformed the Raivola provenance of SL at age 22 in all four test sites established at higher elevations between 52 and 53.2°N in the Cariboo Region (Newsome et al. 2016). The Raviola source originates from low elevations just north of 60°N. Planting this provenance 7-8° south from its origin and at higher elevations also resulted in its relatively poor performance in Alberta compared to other SL sources. In Alaska, the Raivola source grew exceptionally well and better than (native) white spruce and (exotic) lodgepole pine (Alden 2006).
In addition to selections from the identified superior Alberta stands, selections from the species’ natural range would be beneficial to improve performance and genetic diversity. Rehfeldt et al. (1999) concluded that the best seed source of SL for Alberta should be those from locations matching climates of the deployment sites. Our results agree: the Altai Mountain provenance performed well in higher elevations while those from more northern and lower elevation locations performed better at lower elevations in Alberta. Large differences among the seed sources were found in this study corresponding to the elevation and latitude of the test sites. Although historical records preclude verifying the origin elevation, the elevation and latitude of the deployment site are critical when considering deployment of SL.

Siberian larch family variation and performance

Growth performance of SL in Alberta can also be further improved by tree breeding and testing. Significant genetic variance was found for HT and DBH in the open pollinated family test series planted in the province (Table 3). There is very little published information on additive genetic variance in SL. Low and often non-significant heritabilities at age five were found in a Swedish progeny test series (Karlman et al. 2011). In Alberta, all 58 families came from the same region in Russia, thus the genetic variance was not inflated by including families from dissimilar geographic regions. Selection of the top 25% parents would result in an average improvement at age 15 of 7-10% across all five test sites. The five test sites were climatically very diverse, resulting in large genotype by environment interaction. Making different selections for regions based on ecology and climate could further increase gain. Single site results indicate that genetic variance was unstable in the three neighbouring tests planted in the high elevation region close to the Rocky Mountains. The individual tree heritability in these three tests ranged from zero in the test planted at the highest elevation to an estimation of over one with large standard error found...
in the test at the lowest elevation. Site differences would need to be considered when making
selections for that region.

Management implications

Superior early growth of SL in Alberta and differences among the seed sources and open
pollinated families all indicate that this exotic species may be of potential use in commercial
forestry. Introduction of a non-native commercial tree carries risks and benefits and is subject to
a number of challenges (e.g. Anderson et al. 2015, Rivera et al. 2016). Around the world there
are many examples of exotic tree species used in commercial forestry. The most successful is
Monterey pine (*Pinus radiata* D. Don.) in New Zealand, Chile and Australia (Mead 2013). Other
examples include Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in England (Moore 2011), LP in
Sweden (Elfving et al. 2001), Norway spruce (*Picea abies* L.) in Canada (Fullarton and Weng
2013), loblolly pine (*Pinus taeda* L.) in Brazil (Albaugh et al., 2015), Douglas-fir (*Pseudotsuga
tenziesii* (Mirb.) Franco) in New Zealand (Dale 2016) and in the UK (Drewett 2015). The
introduction of SL may increase forest productivity, provide more choices for forest products and
result in greater species diversity of managed forests. Greater species diversity may increase
forest resilience to the detrimental impacts of climate change. LP in British Columbia and
Alberta has suffered a colossal outbreak of mountain pine beetle. It has been suggested that the
outbreak may extend through the LP-JP hybrid region on to JP range (Cooke and Carroll 2017).
SL could be considered as an alternative reforestation species in suitable areas to reduce future
impacts of mountain pine beetle on Alberta forests.

Given its high early growth rate, wood density higher than that of native Alberta conifers, and
high resistance to wood decay, SL is an attractive carbon sequestration species. In the Alberta
site with the oldest comparison data (age 27 Calling Lake) the average SL tree size was 14.4 m
HT, 17 cm DBH and 0.14 m³ over bark stem volume. Adjusted for mortality, the volume per unit
area was 198 m³·ha⁻¹. On the same site with the same planting density and age WS yielded 59.9
m³·ha⁻¹. Assuming average juvenile wood density for SL at 471 kg·m⁻³ (Hakkila and Winter
1974) and 340 kg·m⁻³ for WS (Taylor et al. 1982; Corriveau et al., 1987), and 50% of dry wood
as carbon (Matthews 1993), the SL stand sequestered 171.1 tonnes of CO₂ vs 37.4 tonnes of CO₂
in the WS stand (excluding roots and branches).

Few SL serious pests and diseases have been identified so far in Alberta. Lester and Cerezke
(2001) list larch sawfly (Pristiphora erichsonii Hartig), Armillaria root rot (Armillaria spp.) and
snowshoe hare (Lepus americanus Erxleben) as the most important native pests in the province
for larch, but lacked certainty regarding differences in susceptibility to Armillaria spp. between
SL and native conifer hosts. On several sites in Alaska the larch sawfly and unknown bark
beetles were found (Alden 2006). In Sweden SL plantations have been generally free from major
pest and disease for over 150 years (Karlman 2010).

Before any larger scale introduction is considered, more should be learned about the species in
Alberta to form a basis of a thorough risk and benefit analysis. Information gaps include aspects
such as wood properties, growth and yield analysis, stem form, frequency and size of knots, bark
to wood ratio, seed and seedling production, animal damage, silvicultural options, potential for
hybridization with tamarack, native species displacement, and ecological changes including
potential impacts on natural disturbance (e.g. fire) regimes. Market value analysis should also be
undertaken before any large-scale introduction, as only large-scale deployment would create
market conditions that would spur adoption of a new species in forest management. The already
established SL plantings in Alberta can provide a wealth of information as they age and should
be periodically evaluated for growth, stem quality, presence of pests and diseases, and environmental damage.

Conclusions

In Alberta, SL grew considerably faster, at nearly every test site, than the native LP, WS and JP up to the assessed ages of 27 years. Its survival was slightly lower than that of LP and WS, while forking rates were similar. Significant genetic variation was evident at younger and older test ages both among provenances and families. The performance of this species can be further improved by deploying the best seed sources and the best genotypes as identified in Alberta population and progeny tests. The best seed sources for Alberta were those collected from mature trees of unknown origin planted in Alberta and Saskatchewan.

Acknowledgments

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References


doi.org/10.5558/tfc2015-095


CNFI. 2018. Canada’s National Forest Inventory. Standard reports, Table 16.0, Total tree volume (million m³) by species group and age class in Canada.


Dale, R. 2016. New SWP partnership brings renewed focus on Douglas-fir research.


Fedorkov A. 2014. Vitality and height growth of two Larix species and provenances in a field trial located in north-west Russia. Silva Fennica 48 (1) article ID 1053. 7 p. doi.org/10.14214/sf.1053


IAEARNC. 2009. Interactive agricultural ecological atlas of Russia and neighboring countries.  


www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr096.htm


doi.org/10.1080/02827580510036210

doi.org/10.1139/x99-143

doi.org/10.21750/REFOR.1.13.13

Ruotsalainen, S. 2017. The history of cultivation of exotic tree species in Finland. Natural resources and bioeconomy studies 88/2017. Natural Resources Institute Finland, Helsinki.

doi.org/10.1139/B07-053


Table 1. Siberian larch test location, soil moisture regime (SMR) and soil nutrient regime (SNR), sources tested, experimental design and latest data age.

<table>
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<th>Location (test no)</th>
<th>Test code</th>
<th>SMR, SNR</th>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Elevation (m)</th>
<th>SL populations &amp; families tested*</th>
<th>Design</th>
<th>Latest data age (years)</th>
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<td>Brooks (1)</td>
<td>G138C</td>
<td>subxeric high</td>
<td>50.55</td>
<td>111.85</td>
<td>750</td>
<td>10 (1 Can.)</td>
<td>RCBD, 4 blocks, 3-tree row plots</td>
<td>30</td>
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<tr>
<td>Calling Lake (1)</td>
<td>G139B</td>
<td>mesic moderate</td>
<td>55.27</td>
<td>113.16</td>
<td>639</td>
<td>21 OP families</td>
<td>RCBD, 2 blocks, 10-tree row plots</td>
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<tr>
<td>Clearwater (1)</td>
<td>G308C</td>
<td>mesic moderate</td>
<td>52.02</td>
<td>115.08</td>
<td>1287</td>
<td>2 (1 Can.), 58 OP families</td>
<td>RCBD, 5 blocks, 3-tree row plots</td>
<td>15</td>
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<tr>
<td>Diamond Hills (1)</td>
<td>G308B</td>
<td>mesic moderate</td>
<td>52.62</td>
<td>115.09</td>
<td>998</td>
<td>3 (1 Can.), 53 OP families</td>
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<tr>
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<td>G136F</td>
<td>mesic moderate</td>
<td>52.62</td>
<td>115.09</td>
<td>998</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 9-tree row plots</td>
<td>30</td>
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<tr>
<td>Dry Creek (1)</td>
<td>G308D</td>
<td>mesic moderate</td>
<td>52.19</td>
<td>115.42</td>
<td>1468</td>
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<td>Grande Prairie (1)</td>
<td>G144</td>
<td>subhygic high</td>
<td>55.17</td>
<td>118.80</td>
<td>657</td>
<td>6 (2 Can.)</td>
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<td>Gurtler (1)</td>
<td>G330</td>
<td>subhygic moderate</td>
<td>56.75</td>
<td>117.66</td>
<td>534</td>
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<td>G120A</td>
<td>mesic moderate</td>
<td>59.14</td>
<td>117.57</td>
<td>334</td>
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<td>One 25x5 block plot</td>
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<td>mesic moderate</td>
<td>59.14</td>
<td>117.57</td>
<td>334</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 8-tree row plots</td>
<td>25</td>
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<td>Hay River (3)</td>
<td>G138B</td>
<td>mesic moderate</td>
<td>59.14</td>
<td>117.57</td>
<td>334</td>
<td>14 (4 Can.)</td>
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<td>Site Code</td>
<td>Soil Type</td>
<td>Dominant Forest Type</td>
<td>Latitude</td>
<td>Longitude</td>
<td>Plot Description</td>
<td>Family Count</td>
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<td>Hay River (4)</td>
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<td>moderate</td>
<td>59.14</td>
<td>117.57</td>
<td>2, 30 OP families</td>
<td>RCBD, 2 blocks, 10-tree row plots</td>
<td>27</td>
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<td>Huallen (1)</td>
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<td>moderate</td>
<td>55.28</td>
<td>119.53</td>
<td>3 (1 Can.)</td>
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<td>6</td>
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<td>Mitsue South (1)</td>
<td>G136C</td>
<td>mesic</td>
<td>low</td>
<td>55.10</td>
<td>114.53</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 6-tree row plots</td>
<td>15</td>
</tr>
<tr>
<td>Smoky Lake (1)</td>
<td>G308A</td>
<td>submesic</td>
<td>moderate</td>
<td>54.08</td>
<td>112.25</td>
<td>3 (1 Can.), 58 OP families</td>
<td>RCBD, 5 blocks, 4-tree row plots</td>
<td>15</td>
</tr>
<tr>
<td>Smoky Lake (2)</td>
<td>G136A</td>
<td>submesic</td>
<td>moderate</td>
<td>54.08</td>
<td>112.25</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 8-tree row plots</td>
<td>25</td>
</tr>
<tr>
<td>Smoky Lake (3)</td>
<td>G281</td>
<td>submesic</td>
<td>moderate</td>
<td>54.08</td>
<td>112.25</td>
<td>9</td>
<td>RCBD, 5 blocks, 6-tree row plots</td>
<td>20</td>
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<td>Swartz Creek (1)</td>
<td>G136B</td>
<td>subhydric</td>
<td>very low</td>
<td>53.42</td>
<td>116.50</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 4-tree row plots</td>
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</tr>
<tr>
<td>Swartz Creek (2)</td>
<td>G243A</td>
<td>subhydric</td>
<td>very low</td>
<td>53.42</td>
<td>116.50</td>
<td>2, (1 Can.)</td>
<td>RCBD, 5 blocks, 6-tree row plots</td>
<td>25</td>
</tr>
<tr>
<td>Virginia Hills (1)</td>
<td>G138D</td>
<td>mesic</td>
<td>moderate</td>
<td>54.47</td>
<td>115.85</td>
<td>9</td>
<td>RCBD, 3 blocks, 8-tree row plots</td>
<td>13</td>
</tr>
<tr>
<td>Wandering River (1)</td>
<td>G136G</td>
<td>mesic</td>
<td>moderate</td>
<td>55.20</td>
<td>112.50</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 9-tree row plots</td>
<td>30</td>
</tr>
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<td>Whitecourt Mtn. (1)</td>
<td>G136E</td>
<td>mesic</td>
<td>moderate</td>
<td>54.06</td>
<td>115.79</td>
<td>2 (1 Can.)</td>
<td>RCBD, 5 blocks, 8-tree row plots</td>
<td>30</td>
</tr>
<tr>
<td>Whitecourt Mtn. (2)</td>
<td>G308E</td>
<td>mesic</td>
<td>moderate</td>
<td>54.06</td>
<td>115.79</td>
<td>3 (1 Can.), 44 OP families</td>
<td>RCBD, 5 blocks, 2-tree row plots</td>
<td>15</td>
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<tr>
<td>Whitecourt Mtn. (3)</td>
<td>G243C</td>
<td>mesic</td>
<td>moderate</td>
<td>54.06</td>
<td>115.79</td>
<td>3 (1 Can.)</td>
<td>RCBD, 5 blocks, 6-tree row plots</td>
<td>25</td>
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*OP = open pollinated, Can. = collections from trees of unknown origin growing in Canada.
Table 2. Siberian larch seed sources planted in Alberta field trials sorted by country of origin.

<table>
<thead>
<tr>
<th>Collection location</th>
<th>Code</th>
<th>Country, region</th>
<th>Latitude (°N)</th>
<th>Longitude (°)</th>
<th>SL variety sukaczewii</th>
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</thead>
<tbody>
<tr>
<td>Beaverlodge</td>
<td>BEA</td>
<td>Canada, Alberta*</td>
<td>55.21</td>
<td>-119.42</td>
<td>unknown</td>
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<tr>
<td>Edmonton</td>
<td>EDM</td>
<td>Canada, Alberta*</td>
<td>53.54</td>
<td>-113.49</td>
<td>unknown</td>
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<tr>
<td>Oliver Tree Nursery</td>
<td>OLI</td>
<td>Canada, Alberta*</td>
<td>53.63</td>
<td>-113.32</td>
<td>unknown</td>
</tr>
<tr>
<td>Peace River</td>
<td>PEA</td>
<td>Canada, Alberta*</td>
<td>56.15</td>
<td>-117.42</td>
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</tr>
<tr>
<td>Morden</td>
<td>MOR</td>
<td>Canada, Manitoba*</td>
<td>49.19</td>
<td>-98.1</td>
<td>unknown</td>
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<tr>
<td>Indian Head</td>
<td>IND</td>
<td>Canada, Saskatchewan*</td>
<td>50.52</td>
<td>-103.68</td>
<td>unknown</td>
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<tr>
<td>Kambja</td>
<td>KAM</td>
<td>Estonia*</td>
<td>58.17</td>
<td>26.9</td>
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<td>Piirsalu</td>
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<td>Estonia*</td>
<td>59.07</td>
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<td>Tartu</td>
<td>TAR</td>
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<td>Raivola</td>
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<td>Finland*</td>
<td>60.73</td>
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<tr>
<td>Ivanovo Oblast</td>
<td>IVA</td>
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<td>56.71</td>
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<td>KRA</td>
<td>Russia, south-central Siberia</td>
<td>56.04</td>
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<tr>
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<td>NOV</td>
<td>Russia, south-central Siberia</td>
<td>55.08</td>
<td>82.8</td>
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<td>Altai Mountains</td>
<td>ALT</td>
<td>Russia, southern Siberia</td>
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<td>Tuva</td>
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<td>Russia, southern Siberia</td>
<td>51.83</td>
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<td>Abzelilovsk</td>
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<td>Bashkir</td>
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*SL exotic
Table 3. Seed source survival by test location.

<table>
<thead>
<tr>
<th>Seed source*</th>
<th>Brooks</th>
<th>Clear water</th>
<th>Diamond Hills</th>
<th>Dry Creek</th>
<th>Gurtler</th>
<th>Hay River</th>
<th>Huallen</th>
<th>Mitsue South</th>
<th>Smoky Lake</th>
<th>Swartz Creek</th>
<th>Virginia Hills</th>
<th>Wandering River</th>
<th>Whitecourt Mnt</th>
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<tr>
<td>ABZ</td>
<td>75%</td>
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<td>35%</td>
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<td>83%</td>
<td>87%</td>
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<tr>
<td>ALT</td>
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<td>88%</td>
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<td>56%</td>
<td>35%</td>
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* See Table 2 for seed source codes and origin
Table 4. Variance components as percentage of the total variance, heritabilities and type B genetic correlations for height at age 15.

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<th>Site</th>
<th>$\sigma_f^2$ ($\pm$)</th>
<th>$\sigma_p^2$</th>
<th>$\sigma_{zf}^2$</th>
<th>$\sigma_e^2$</th>
<th>$h_t^2$ ($\pm$)</th>
<th>$h_f^2$ ($\pm$)</th>
<th>$r_b$ ($\pm$)</th>
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<td>Clearwater</td>
<td>6.09 ± 2.86</td>
<td>0.004</td>
<td>93.91 ± 5.65</td>
<td>0.24 ± 0.11</td>
<td>0.41 ± 0.12</td>
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<tr>
<td>Diamond Hills</td>
<td>27.30 ± 8.40</td>
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<td>72.70 ± 6.53</td>
<td>1.09 ± 0.27</td>
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<td>Dry Creek</td>
<td>2.86 ± 2.38</td>
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<td>97.14 ± 6.07</td>
<td>0.38 ± 0.12</td>
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<td>Smoky Lake</td>
<td>9.54 ± 2.79</td>
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<td>90.46 ± 4.16</td>
<td>0.38 ± 0.10</td>
<td>0.48 ± 0.12</td>
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<tr>
<td>Whitecourt Mtn.</td>
<td>9.48 ± 4.51</td>
<td>0.003</td>
<td>90.52 ± 7.21</td>
<td>0.38 ± 0.17</td>
<td>0.59 ± 0.09</td>
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<tr>
<td>All sites</td>
<td>3.87 ± 1.33</td>
<td>&lt;0.001</td>
<td>4.91 ± 1.41</td>
<td>0.15 ± 0.05</td>
<td>0.44 ± 0.12</td>
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</tbody>
</table>
Figure 1. Locations of Siberian larch trial sites in Alberta and local species’ distributions. LP = lodgepole pine, JP = jack pine, WS = white spruce.

Figure 2. Survival (SURV), height (HT) and diameter at breast height (DBH) of Siberian larch (SL) as a proportion of lodgepole pine (LP) survival, height and diameter by test location.

Figure 3. Survival (SURV), height (HT) and diameter at breast height (DBH) of Siberian larch (SL) as a proportion of white spruce (WS) survival, height and diameter by test location.

Figure 4. Survival (SURV), height (HT) and diameter at breast height (DBH) of Siberian larch (SL) as a proportion of jack pine (JP) survival, height and diameter by test location.

Figure 5. Height of Siberian larch seed sources by elevation of Alberta test sites, relative to the Raivola source. The average data age is 20 years. See Table 2 for seed source codes and origin.
Figure 1. Locations of Siberian larch trial sites in Alberta and local species’ distributions. LP = lodgepole pine, JP = jack pine, WS = white spruce.
Figure 2. Survival (SURV), height (HT) and diameter at breast height (DBH) of Siberian larch (SL) as a proportion of lodgepole pine (LP) survival, height and diameter by test location.
Figure 3. Survival (SURV), height (HT) and diameter at breast height (DBH) of Siberian larch (SL) as a proportion of white spruce (WS) survival, height and diameter by test location.
Figure 4. Survival (SURV), height (HT) and diameter at breast height (DBH) of Siberian larch (SL) as a proportion of jack pine (JP) survival, height and diameter by test location.
Figure 5. Height of Siberian larch seed sources by elevation of Alberta test sites, relative to the Raivola source. The average data age is 20 years. See Table 2 for seed source codes and origin.