Should we plant trees further north or at higher elevation to compensate for climate warming? An evaluation of frost risks.

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Extended abstract with figures and tables

Rationale: Moving species and their populations poleward and upward in elevation, also referred to as human assisted migration, has been proposed as an adaptation strategy to mitigate climate change impacts. However, for long-lived organisms, such as trees, seedlings and young individuals may have to be exposed to colder than normal environments in anticipation of climate warming over the decades or centuries of their life span. In a case study for western Canada, where approximately 200 million seedlings are planted every year, forest managers are already moving some species and their populations to more northern locations or to higher elevation bands to compensate for observed and projected climate change. This could lead to frost damage of planted seedlings not adapted to cold environments.

Objective: In this study, we quantify frost risks to seedlings or saplings when moved to areas that are cooler by approximately 2°C at present in anticipation of future climate warming. This represents an approximately 350km shift poleward, or a 550m shift in elevation. These shifts also represent a move of planting stock from current seed zones used in reforestation to adjacent northern or higher elevation zones. Specifically, we evaluate the probability and severity of frost events in the 30 days following budbreak in spring, and the probability and severity of frost events in a 30-day time window before the fall equinox.

Methods: Working with four important commercial tree species of British Columbia and Alberta, Douglas-fir, lodgepole pine, interior spruce and western larch, we evaluate movement of seed sources and breeding populations among adjacent seed zones that currently govern reforestation activities (Fig. 1). The study area has considerable latitudinal and elevation gradients ranging from mean annual temperatures of 10°C in the South of British Columbia to -15°C in high mountains or Alberta’s north (Fig. 2). However, the average temperature of seed zones where trees are commercially planted in Alberta only spans from -1.1 to 2.3°C (a 3.4°C range), representing sub-boreal and boreal forests east of the Rocky Mountains with a mild latitudinal temperature gradient (Fig. 2). Average temperatures of seed zones in British Columbia, with a more heterogenous environment, span from -0.3 to 7.2°C (a 7.5°C range).

Frost risks to seedlings planted in these zones are evaluated with interpolated daily climate data at 1km resolution between 1980 and 2019, i.e. approximately 15,000 climate surfaces per climate variable obtained from the U.S. Department of Energy's Office of Science (DAYMET database). The date where trees break buds in spring is estimated as the day of year where degree days above 5°C reach a heatsum of 100 degree days, derived for each year from daily average temperature grids. We then recorded the coldest late spring frost event in each year in the 30 days following the estimated day of budbreak, using DAYMET grids of daily minimum nighttime temperatures. To evaluate the risk of early fall frosts, we similarly recorded the coldest frost event in the 30 days prior the fall equinox. We use this fixed interval in fall since the date of the onset of dormancy is primarily controlled by daylength in temperate trees, while the timing of budbreak is driven by spring temperatures.

Results & Discussion: The primary source of information to make inferences in this study is a geographic evaluation of the probability of late spring frosts and early fall frosts in British Columbia and Alberta. For example, we can query the probability of experiencing a ≤ -5°C late spring frost in any given year within a 30-day window following budbreak, or within 30 days before the fall equinox (Fig. 3). We can also visualize the distribution of the coldest frost event within these 30-day windows across 39 years for specific seed zones (Fig. 4). In this example for three lodgepole pine seed zones, late spring frost risks for a southern versus northern seed zone (NE low vs. PG low) are similar (Fig. 4, upper left panel). In contrast, seedling planted in a higher elevation zone (NE low vs. NE high) experience a considerably increased frequency and severity of late-spring frost events (Fig. 4, lower left panel). Note, that is despite breaking bud later (at degree day 100) at the colder, high elevation planting site.

Frost risks in fall are generally higher than in spring in this analysis, but this is due to setting arbitrary reference dates (30 days before equinox, 30 days after degree day 100) to sample frost events. An interpretation of differences in frost risks in spring versus fall is therefore not meaningful. Rather, the relevant comparisons are those among seed zones. Both spring and fall frost comparisons show that the increase in unseasonal frosts is higher for transfers to higher elevations than to higher latitudes. The increases in risk are driven by higher variability in cold events (wider distributions, lower peaks) for the high-elevation seed zones. For similar elevation bands, the more northern seed zones tend to have slightly lower climate variability (e.g., slightly narrower distribution and higher peak for the PG zone).

To expand this analysis to all transfers among adjacent seed zones for all four species across British Columbia, we report the changes in probabilities, represented by colored areas under the curve in Fig. 4 as numerical values in Table 1 and 2. Changes in frost probabilities due to assumed seed transfers are highlighted with a gray scale. Similar to the example highlighted in Fig. 4, we find that the risk of a late spring frost or early fall frost does not change in a major way, when planting stock is moved to adjacent seed zones toward the north (Table 1). In contrast, moving planting stock toward higher elevation generally leads to a substantial increase in exposure to both late spring frosts and early fall frosts (Table 2). On average, the probability of experiencing a late spring frost ≤ -5°C following budbreak increases from 0.5% to 9.4% across all seed zones. The change for fall frosts as a consequence of elevation transfers is 32% (from an average 7% at lower seed zones to an average 39% at adjacent high elevation seed zones). As in the detailed example shown in Fig. 4, this effect is due to the year-to-year variability of frost events being considerably larger at higher elevation in both the spring and fall windows that we evaluated, while for latitudinal transfers, the expected limited increase in frost risk due to temperature shifts to a colder area.

Conclusions and applications: In order to implement assisted migrations prescriptions for commercial forest trees in western Canada, this climatic risk analysis suggests that transfers toward the north are preferable to transfers up in elevation. In transfers toward the north, there are virtually no changes to late spring and early fall frost risks compared to the status quo of not moving seed sources. Assuming a temperature-controlled day of budbreak, and no changes in daily temperature variability under climate change, late spring frost risks of northwards transfers should also remain identical to historic probabilities. Regarding late fall frost risks under climate change, the already moderate increase in risk due to northward movement could be reduced by climate warming. However, this assumes that trees do not respond to northward transfers by changing the date of growth cessation. This would apply if the daylength trigger for the onset of dormancy is at around 12 hours, i.e. the same trigger would be observed at the same time (fall equinox) at different latitudes.

Table 1. Changes to frost risks for northward latitudinal transfers that represent a transfer to environments approximately 2°C colder in mean annual temperature (MAT). Late spring frost events are defined as nights < -5°C in a 30-day window following the day of year where growing degree days reach 100 (proxy for budbreak). Early fall frost events are nights < -5°C in a 30-day window before the fall equinox (proxy for onset of dormancy). Examples of risk comparisons among seed zones for four species: df, Douglas-fir; lp, lodgepole pine; wl, western larch; ws, interior spruce).

		Transfer difference			Late spring frost risks (Probability of ≤ -5°)		Early fall frost risks (Probability of ≤ -5°)	
Species	Seed zone transfer	MAT (°C)	Elev (m)	Lat (km)				
df	CT low to PG low	-1.2	- 113	**+ 261**	0.1 to 0%	0%	12 to 10%	-2%
df	EK low to PG low	-1.2	- 245	**+ 466**	0.1 to 0%	0%	4 to 10%	+7%
lp	AB c to j	-2.8	- 219	**+ 300**	0.2 to 0.7%	+1%	11 to 28%	+16%
lp	EK low to CP low	-1.9	- 252	**+ 580**	0.1 to 0.1%	0%	4 to 12%	+8%
lp	NE low to PG low	-1.2	- 49	**+ 301**	0.7 to 0%	-1%	4 to 9%	+5%
lp	PG low to CP low	-1.4	- 75	**+ 285**	0 to 0.1%	0%	9 to 12%	+3%
lp	TO low to BV low	-2.8	- 48	**+ 449**	0.7 to 0.2%	0%	7 to 8%	+1%
ws	AB d to g2	-2.3	- 149	**+ 269**	0.2 to 0.6%	0%	11 to 24%	+14%
ws	AB d1 to e1	-1.5	- 229	**+ 170**	1.2 to 2.4%	+1%	11 to 7%	-4%
ws	AB e to e1	-1.0	- 129	**+ 149**	3.4 to 2.4%	-1%	10 to 7%	-3%
ws	AB e2 to d1	-1.3	- 19	**+ 199**	3.4 to 1.2%	-2%	14 to 11%	-3%
ws	AB g1 to g2	-2.0	- 67	**+ 214**	0.5 to 0.6%	0%	14 to 24%	+10%
ws	NE low to PG low	-1.8	- 22	**+ 395**	0 to 0.1%	0%	0 to 11%	+11%
ws	PG low to PR low	-2.5	- 257	**+ 413**	0.1 to 0%	0%	11 to 7%	-4%
ws	TO low to BV low	-1.8	- 55	**+ 389**	2.2 to 0.6%	-2%	18 to 10%	-9%
Average change		- 1.9	-129	**+ 323**		0%		+3%

Table 2. Changes to frost risks for transfers to higher elevations that represent a transfer to environments approximately 2°C colder in mean annual temperature.

		Transfer difference			Spring risk change (Probability of ≤ -5°)		Fall risk change (Probability of ≤ -5°)	
Species	Seed zone transfer	MAT (°C)	Elev (m)	Lat (km)				
df	M low to M high	-1.8	**+ 654**	+ 23	0.3 to 11%	+11%	0 to 15%	+15%
df	NE low to NE high	-2.1	**+ 547**	- 25	0 to 3%	+3%	1 to 14%	+13%
lp	BV low to BV high	-1.1	**+ 359**	-3	0.2 to 14%	+13%	8 to 61%	+53%
lp	CP low to CP high	-1.6	**+ 494**	+38	0.1 to 14%	+13%	12 to 67%	+55%
lp	EK low to EK high	-2.7	**+ 631**	- 1	0.1 to 1%	+1%	4 to 26%	+22%
lp	NE low to NE high	-2.8	**+ 689**	- 1	0.7 to 11%	+10%	4 to 28%	+24%
lp	NS low to NS high	-2.7	**+ 752**	+ 4	1.1 to 22%	+21%	11 to 76%	+65%
lp	PG low to PG high	-1.9	**+ 529**	-15	0 to 8%	+8%	9 to 47%	+39%
lp	TO low to TO high	-2.4	**+ 617**	-10	0.7 to 7%	+6%	7 to 33%	+26%
wl	NE low to NE high	-2.5	**+ 638**	- 23	1.1 to 10%	+9%	6 to 27%	+21%
ws	BV low to BV high	-1.2	**+ 431**	- 23	0.6 to 8%	+7%	10 to 40%	+30%
ws	NE low to NE high	-2.3	**+ 558**	+ 7	0 to 4%	+4%	0 to 18%	+17%
ws	PG low to PG high	-1.4	**+ 492**	+ 20	0.1 to 2%	+2%	11 to 37%	+26%
ws	TO low to TO high	-2.2	**+ 511**	- 6	2.2 to 17%	+15%	18 to 55%	+37%
Average change		- 2.0	**+ 564**	-1		+9%		+32%

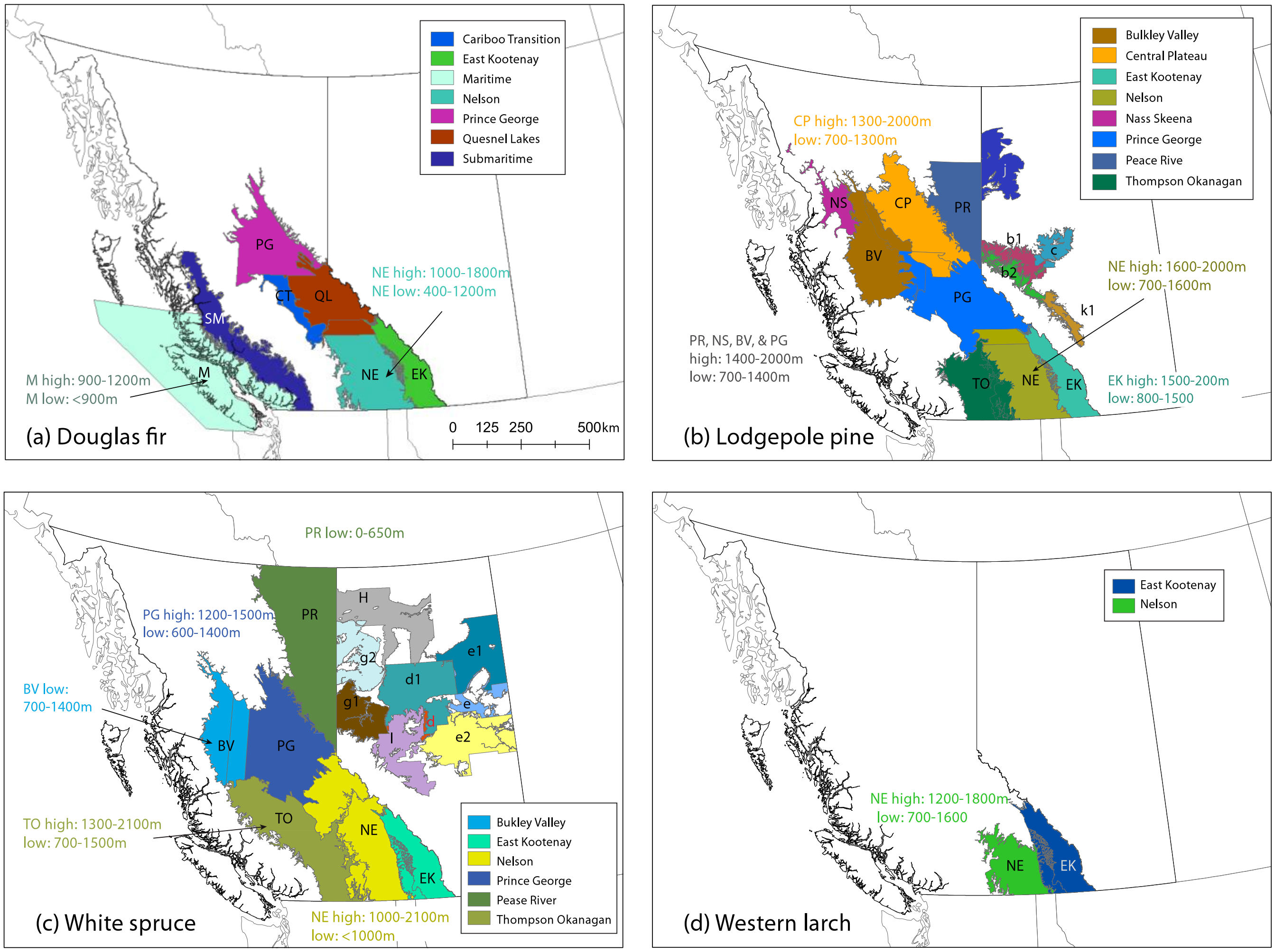

Figure 1. Seed zones of four commercial forestry species evaluated in this analysis.

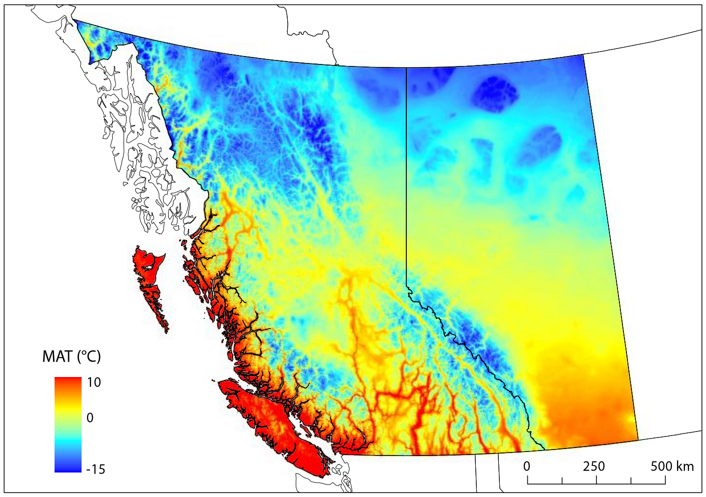

Figure 2. Mean annual temperature gradients across British Columbia and Alberta.

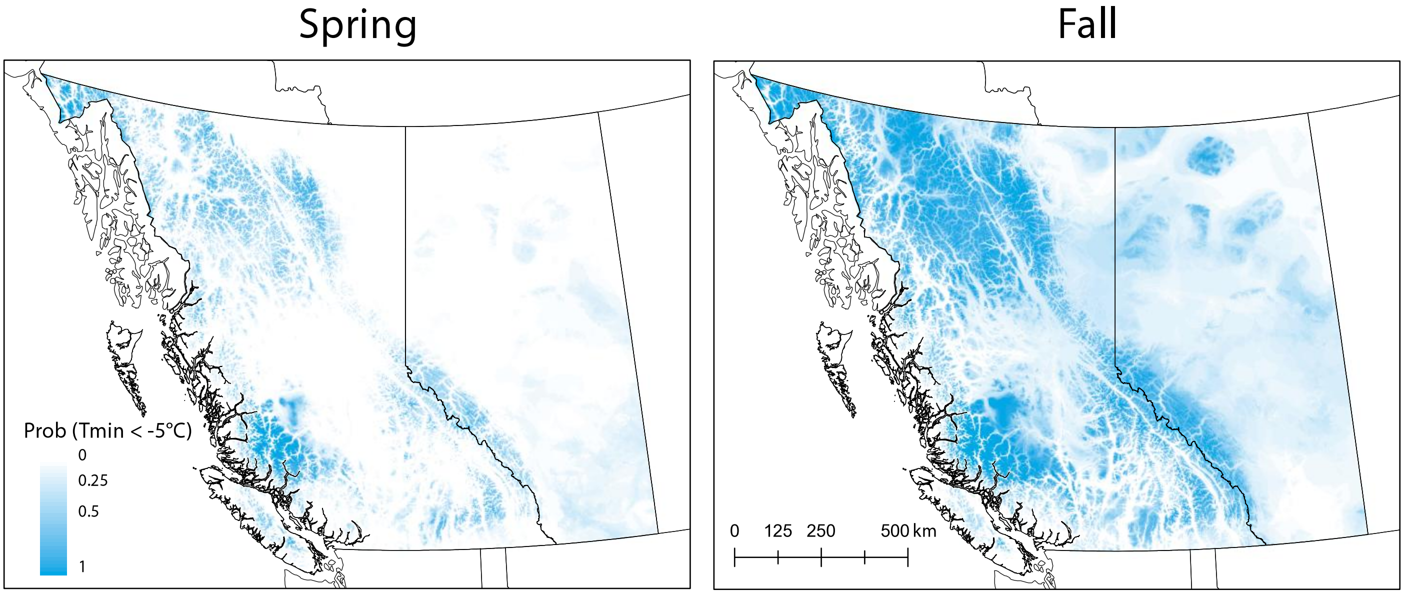

Figure 3. Probability of experiencing a late spring frost or an early fall frost in any given year. Late spring frost events are defined as nights ≤ -5°C in a 30-day window following the day of year where growing degree days reach 100 (proxy for budbreak). Early fall frost events are defined as nights ≤ -5°C in a 30-day window prior the fall equinox (proxy for onset of dormancy).

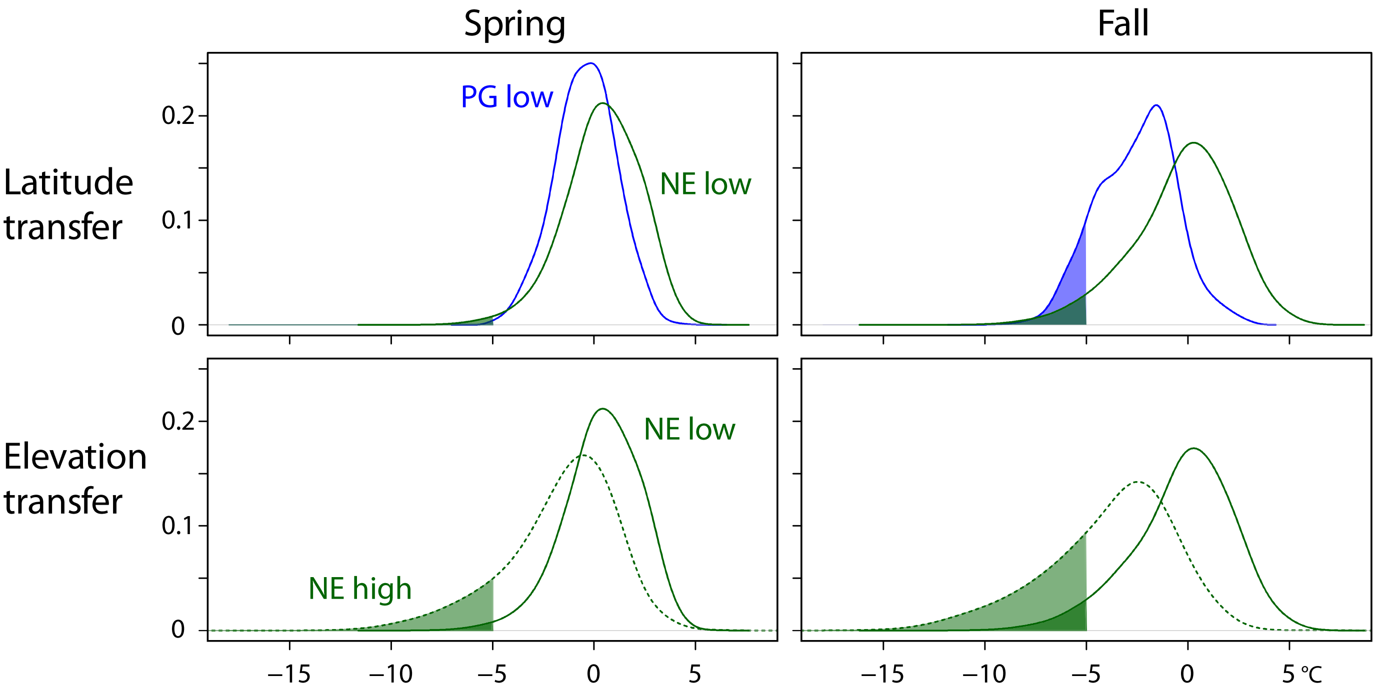

Figure 4. Histograms of the probability the coldest late spring frost event (left panel) or the coldest early fall frost event (right panel) exceeding a threshold of ≤ -5°C (highlighted by a colored area) for three lodgepole pine seed zones. The seed zone pairs represent a 350km northward transfer (NE low to PG low) and a 550m elevation transfer (NE low to high). Histograms in all cases are for daily temperatures from 1980 to 2019.