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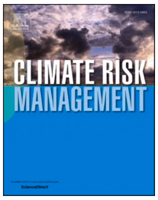

Assisted migration poleward rather than upward in elevation minimizes frost risks in plantations

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ABSTRACT

When assisted migration is used to address climate change, tree seedlings may have to be moved to substantially colder environments in anticipation of climate warming over their life span. Here, we evaluate frost risks for four economically important forest tree species of western Canada, Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), interior spruce (*Picea glauca, P. engelmannii,* and their hybrids), and western larch (*Larix occidentalis*), when moved to adjacent northern and higher elevation seed zones that are cooler by approximately 2 °C. Changes to risks of damaging frosts among seed zones are evaluated during two 30-day periods, after dormancy release in spring and before onset of dormancy in fall, assuming a temperature-dominated day of bud break and a critical photoperiod-controlled onset of dormancy in fall. Based on daily interpolated climate data between 1980 and 2019, we find that late spring and early fall frost risks do not change significantly for transfers toward the north (<1 percentage point in most cases). In contrast, moving planting stock toward higher elevation generally leads to a substantial increase in exposure to unseasonal frosts (late spring frosts: 0.5% to 9.4%, early fall frosts: 0.8% to 17.1%). We conclude that transfers toward the north are preferable to transfers up in elevation in reforestation of these tree species in western Canada.

1. Introduction

Tree species and their populations are usually genetically adapted to the historical local climate conditions where they occur (e.g., Morgenstern, 1996). In recognition of local genetic differentiation of populations, reforestation activities are typically governed by seed zones or seed transfer restrictions to minimize the risk of maladaptation, based on the assumption that local seed sources are best adapted (e.g., Campbell, 1986; O'Neill and Aitken, 2004). Most jurisdictions in North America have historically divided their forested land base into zones that are climatically, edaphically, and ecologically fairly homogeneous, and only seed sources that originate within these regions may be planted in the same region. Such seed transfer restrictions through seed zones govern reforestation activities in Alberta (Downing and Pettapiece, 2006) and in British Columbia, Canada (MFLNRO, 2018) as well.

However, fixed geographic seed zone systems no longer are a valid management approach under climate change, due to their underlying assumption that local seed sources are optimally adapted to their corresponding environments. Since the beginning of the 20th century, mean annual temperatures have increased by 1.3 °C across British Columbia and Alberta (Wang et al., 2016), which

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causes a mismatch between new climate conditions, and the optimal environment for current ecosystems, the climatic tolerances of the species they contain, and genetic adaptations of their populations to local environments (Etterson et al., 2020; Gray and Hamann, 2013). This mismatch has already caused major disruptions to forest health and productivity in western Canada (e.g., Chaste et al., 2019; Chen and Luo, 2015; Comeau et al., 2021; Michaelian et al., 2011).

To address this issue, it has been proposed that tree species and their populations be moved northward and upward in elevation, also referred to as assisted migration (Peters and Darling, 1985). In the context of forestry, this can relatively easily be implemented as part of regular reforestation activities in managed forests (Aitken and Bemmels, 2016; Gray et al., 2011; McLane and Aitken, 2012; Pedlar et al., 2021). Moving seed sources poleward and to higher elevations, where planting environments are cooler, would help to compensate for climate warming that has already occurred. This will increase the likelihood that climate conditions to which local populations are adapted match current and future growing environments, and thereby maintain forest health and productivity for the coming decades. Assisted migration prescriptions within and outside of current species ranges are already being implemented in western Canada by moving some species and their populations (e.g., western larch, *Larix occidentalis*) to more northern locations or to higher elevation bands across seed zone boundaries to compensate for observed and projected climate change (Marris, 2009; MFLNRO, 2018; Natural Resources Canada, 2020; O'Neill, 2017).

However, the benefits of assisted migration prescriptions have to be balanced against the inherent risk of major changes to management practices (Hotte et al., 2016). One potential problem that arises for long-lived tree species is that they may experience substantial climate change over the course of their lifetime. In order to match their optimum climatic niche with their most productive growing period, seeds and seedlings may have to be exposed to colder than optimal environments in anticipation of climate warming over the decades or centuries of their life span. Therefore, the risk of potential frost damage to planting stock that is to be moved to colder locations needs to be balanced against the benefit of more mature trees being better adapted to warmer growing environments decades later. For example, a seedling established in central Alberta in 2020 would ideally come from a source location that is 1.3 °C warmer to account for observed climate change since the beginning of the 20th century. By the age of 20, the best matching seed source would originate from climate conditions about 2.5 °C warmer than the current planting site condition, and by the age of 50 the optimal source location would be approximately 3.5 °C warmer, according to CMIP5 multi-model climate projections (Knutti et al., 2013). It

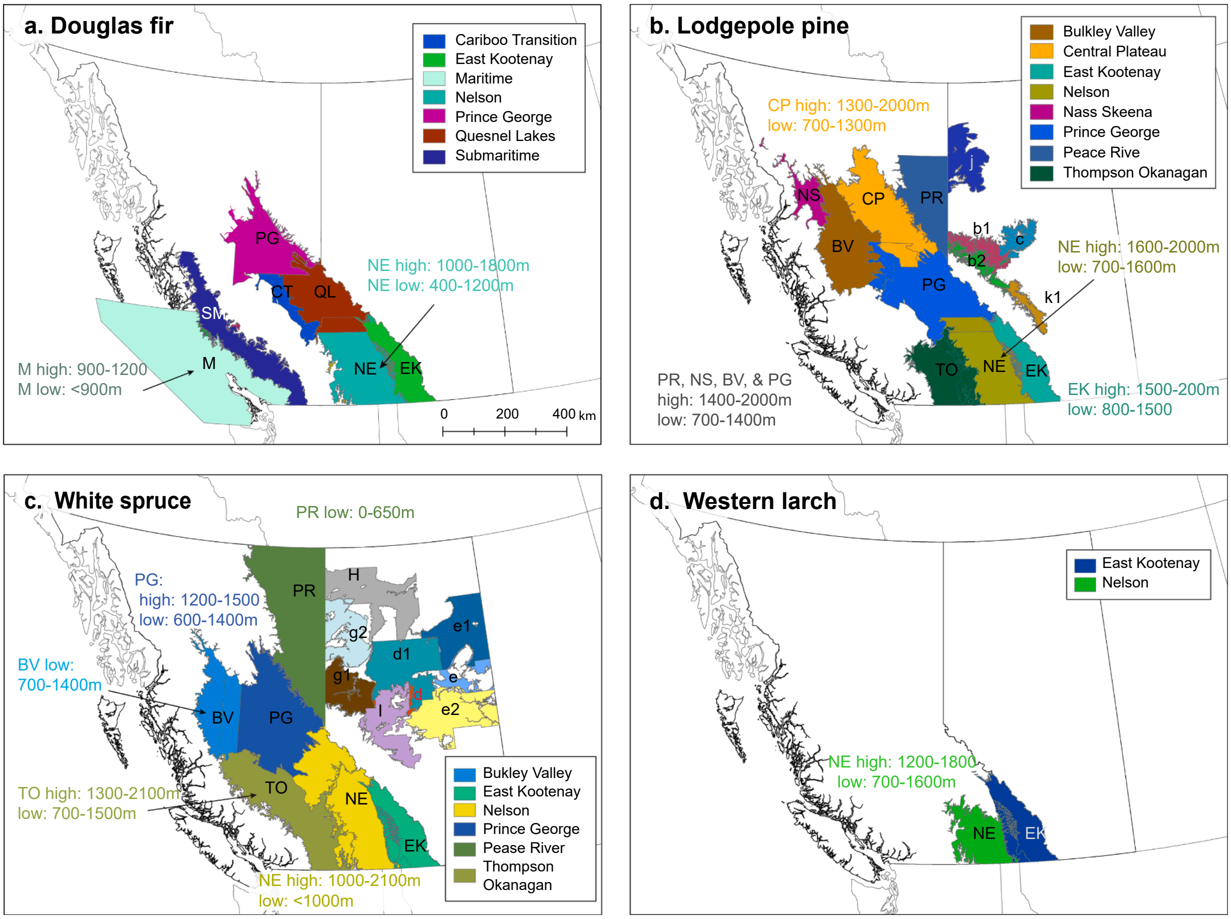

Fig. 1. Seed zones of four economically important forestry species of the Canadian provinces British Columbia and Alberta evaluated in this analysis.

would therefore be helpful to understand how far we can move planting stock to colder environments, without exposing them to unreasonable frost risks at early life stages.

Temperate trees use environmental cues closely related to seasonal changes (e.g., photoperiod and thermal conditions) to synchronize their growing period with favorable environmental conditions (Rathcke and Lacey, 1985). Local populations typically evolve timing of active growth so that evolutionary growth-survival trade-offs are optimized (Loehle, 1998). A late bud break would protect young leaf tissue from late spring frosts, but would also reduce the growing season length and the competitiveness with other species or differently adapted individuals. For temperate plants, the timing of bud break is usually controlled through a mechanism that accumulates temperature exposure above a base temperature up to a species- and population-specific heat sum requirement. The timing of the onset of dormancy and development of frost hardiness in fall is primarily controlled by photoperiod in most boreal and temperate tree species, (e.g., Ekberg et al., 1979; Oleksyn et al., 1992), although temperature and internal circadian clocks can contribute of fall phenology as well (Cooke et al., 2012).

Here, we quantify frost risks for geographic seed zones of four important commercial conifer species of British Columbia and Alberta, Canada: the coastal and interior varieties of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* and var. *glauca* (Mirb.) Franco), lodgepole pine (*Pinus contorta* Douglas var. *latifolia* (Engelm.) Critchfield), interior spruce (a species complex of *Picea glauca* (Moench) Voss, *P. englemannii* Parry ex Engelm. and their hybrids), and western larch (*Larix occidentalis* Nutt.), when moved to adjacent northern and higher elevation seed zones that are cooler by approximately 2 °C. Specifically, we evaluate the probability and severity of frost events in the 30 days following an approximated day of bud break in spring, and the probability and severity of frost events approximately 30 days before an estimated onset of dormancy in fall. The objectives of this analysis are to (1) determine the safety of assisted migration options by determining the probability of frost events in origin and target seed zones for 14 elevation and 15 latitude transfers, (2) to provide general guidance on how to minimize the risk of frost damage or plantation failure when planting stock is moved to colder environment in assisted migration prescriptions to address climate change.

2. Methods

2.1. Study area

In this study, we evaluate late spring frost and early fall frost risks for four important commercial tree species of British Columbia and Alberta: Douglas-fir, lodgepole pine, interior spruce, and western larch. We evaluate changes to frost risks due to the movement of planting material to adjacent northern and higher elevation seed zones for orchard seed from tree improvement programs (Fig. 1). In British Columbia species-specific “seed planning zones” are divided into elevational bands which are known as “seed planning units” (O’Neill, 2008; British Columbia Government, 2019). In Alberta, a similar system is referred to as “controlled parentage program regions”. Here, we refer to them as “seed zones” that were evaluated in this study (Fig. 1).

The study area has considerable latitudinal and altitudinal variation in climate, with mean annual temperature of individual 1 km^2 grid cells ranging from + 10 °C in southern 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 range 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 heterogeneous environment, span from –0.3 to + 7.2 °C (a 7.5 °C range).

2.2. Frost risk metrics

We evaluate risks of late spring frost and early fall frosts that may damage living tissue during periods where the plant is not fully hardened in winter dormancy. In boreal and sub-boreal ecosystems, bud break in spring typically occurs during April and May (e.g.,

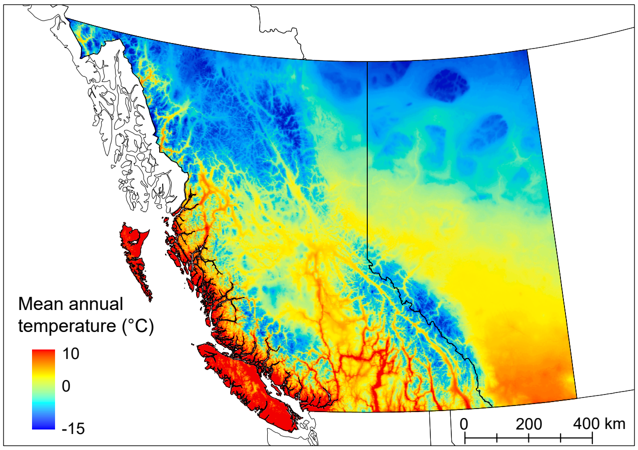

Fig. 2. Mean annual temperature for the 1961 to 1990 normal period across the Canadian provinces British Columbia (left) and Alberta (right).

Glerum, 1973), which is preceded by a dormancy release and dehardening process. However, the timing can vary substantially from year to year and also depends on the microclimate of specific locations. In general, the timing of bud break correlates well with accumulated growing degree days (also referred to as a heat sum), which is calculated as cumulative value of the daily average temperature (in units of °C) above a given base temperature. Usually, a base temperature of 0 to 5 °C best predicts bud break for boreal and temperate trees (e.g., Rathcke and Lacey, 1985). Daily temperature values above the base temperature are added cumulatively over time, normally starting with zero value on January 1st, to describe the heat sum for any day of the year.

To arrive at heat sum metrics that can be used to describe subsequent spring frost risks, we make the assumption that trees need to avoid a certain severity of late spring frost events that may vary among species. To cover a range of late spring frost events that may damage plants at different de-hardening stages, we used the frost event severities of − 5, −10, and − 15 °C. Note that these frost event severities were observed at standard weather station locations that are situated in open field conditions and would only serve as a proxy for actually damaging frost event values at the microsite where a plant is situated. Because our analysis relies on a relative comparison of frost risks of a warmer source region (where seeds are collected) to a cooler target region (where planting stock may be used for reforestation), specific biotic and environmental factors that contribute to frost damage do not need to be explicitly modeled, as they are assumed to be comparable between the source and target seed zones.

For each of the − 5, −10, and − 15 °C frost event severities, we screened for heat sum values across the study area, using both a base temperature of 0 °C and 5 °C, where frost risks are just above zero for the subsequent 30 days (i.e., implying a bud break timing where frost risks are just avoided at the beginning of the available growing season). The heat-sum value that leads to a low but non-zero frost risk differs for different base temperatures and different frost severity values. A search was carried out for 10-degree-day value increments of candidate heat sum values. For each candidate heat sum value an empirical probability of a subsequent frost event below − 5, −10, and − 15 °C was calculated based on a 40-year daily minimum temperature record of interpolated weather station data (see below for details on climate data). Empirical probabilities of late spring frost risks for a 30-day window following estimated bud break were calculated for all seed zones at a 1-km^2 grid cell resolution, using interpolated daily climate data for the last 40 years. A 30-day window was sufficient to capture virtually all late spring-frost events after the predicted bud break. The following heat sum values were chosen, so that no seed zone was free of the risk of experiencing a frost event by a large margin for the purpose of comparing frost risks among seed zones: (1) 40 growing degreedays above a base temperature of 0 °C to avoid − 15 °C frost events, (2) 40 growing degreedays above a base temperature of 0 °C to avoid − 10 °C frost events, (3) 20 growing degreedays above a base temperature of 5 °C to avoid − 10 °C frost events, (4) 100 growing degreedays above a base temperature of 5 °C to avoid − 5 °C frost events.

To assess fall frost risks, we have to assume that different species may respond to different photoperiod cues to initiate the onset of hardening in fall (Rathcke and Lacey, 1985). Although temperature plays a modifying role in the onset of hardening, day length and temperature are confounded and cannot be separately modeled outside of experimental situations. We calculated fall frost probabilities during 30-day periods after night length exceeded 9, 10, and 11 h for each seed zone in our study area. The implied frost risk severity that would be avoided was similarly determined as for spring frost risks based on a 40-year daily minimum temperature record of interpolated weather station data, choosing a frost severity for which no seed zone was risk-free by a large margin (implying a timing of the onset of dormancy so that frost risks are just avoided at the end of the available growing season). The value was − 5 °C for a night length of 9 h, −8 °C for a night length of 10 h, and − 10 °C for a night length of 11 h. Subsequently, probabilities of experiencing these frost severities in the 30-day period following the critical night length were calculated for each 1 km^2 grid cell of a seed zone based on a 40-year daily minimum temperature record of interpolated weather station data.

2.3. Climate data

We calculated frost risks based on interpolated daily climate data obtained from the U.S. Department of Energy's Office of Science (*https://daymet.ornl.gov*). The DAYMET database includes approximately 15,000 daily climate grids per climate variable since 1980 for North America at 1-km resolution in Lambert Conformal Conic projection (Thornton et al., 2014). We used automated batch downloading supported by the Daymet Single Pixel Extraction Web Service API (*https://daymet.ornl.gov/web_services*) to extract 1.6 million 1 km^2 gridded cells for the study area of British Columbia and Alberta in Universal Transverse Mercator (Zone 11) projection. The climate variables we used were daily maximum and minimum temperatures for 40 years from January 1, 1980 to December 31, 2019. All degree day-related calculations were performed based on average daily temperatures. Frost events were parsed based on minimum night-time temperatures. Sample scripts for calculating probability of late spring frost and early fall frost events for the R programming environment (R Core Team, 2016) are provided as Appendix A.1.

Seed zones were also characterized for longer-term climate normal periods to compare their average temperatures. For this purpose, we calculated the 1961–1990 normal temperature by averaging values of gridded climate data points for each seed zone, estimated with the ClimateNA database and software package (*http://tinyurl.com/ClimateNA*, Wang et al., 2016). Adjacent seeds zones with approximate differences of 2 °C in mean annual temperature were evaluated for frost risk changes under potential assisted migration prescriptions, but the analysis is based on a historical frost risk comparison. We do not estimate the change of frost risks under climate change in this study, which would also have to include estimations of plant phenology response under climate change.

As a check for the validity of our conclusions, we also directly evaluated daily weather station data obtained by the Government of Canada (*http://climate.weather.gc.ca*). While forestry seed zones are generally not well represented by weather station coverage, we wanted to confirm that general frost risk patterns associated with latitude and elevation that we inferred from interpolated data products used in this study are consistent with those observed in raw weather station data. This validation is provided as Table A.2, and shows that weather stations located at higher elevations have greater temperature variance in spring and fall than low elevation stations, and northern Alberta has a lower temperature variance than southern Alberta.

3. Results & discussion

3.1. Frost probability landscapes

We describe frost risks with an emphasis on the latest spring frost and earliest fall frost events, i.e., the avoidance of –5 °C frost events, because results of our analysis indicated that avoidance of –8 °C, –10 °C, and –15 °C events generally showed similar patterns. The analysis for the latter thresholds is provided as supplemental information (Tables A.3 to A.6). Based on 40 years of daily temperature records, the landscapes of probabilities for late spring frost risks and early fall frost risks are broadly similar, primarily following elevational gradients (Fig. 3). For early fall frost risks, the expectation is that higher elevation locations at the same latitude should have higher frost risks because they are colder than lower locations for a given day length. In contrast, comparing northern versus southern locations at similar elevations, the expectation would be no change in risks. The 9-hour night length threshold that defines the start of our fall frost time interval would occur later at more northern locations, but at the time of identical night length, frost risks should be comparable at different latitudes. We find, in fact, no latitudinal gradient in early fall frost risk for the 30-day period subsequent to a 9-hour critical night length to initiate dormancy, as can be seen for low-elevation areas of British Columbia and Alberta (Fig. 3, right panel). The observed fall frost risk pattern appears to be largely determined by altitude differences across the study area.

The landscape of spring frost probabilities is slightly different. First, elevational differences are not as pronounced as for fall frosts (less red in Fig. 3, left panel). In addition, there is a slight decline in spring frost risks from south to north in low-elevation areas of Alberta (yellow to gray in Fig. 3 left panel). The expectation of geographic patterns for the spring frost risk map is uniform with no elevational or latitudinal trends, except at very high elevation where the frost-free period is less than our 30-day monitoring period (Fig. 3, dark red). This is because we calculate the frost risks for varying time intervals after a 100 growing degree day threshold is reached. Thus, for a colder northern or higher elevation location, the time interval that we screen for frost events occurs later, because the heat sum value is reached later. In principle, screening a later time period for late spring frosts may compensates for generally colder climate conditions with respect to changes in frost risks.

We do, however, find clear elevational changes in late spring frost risks, with a similar pattern albeit less pronounced than in fall (Fig. 3). The observed latitudinal and altitudinal gradients in spring frost risks could be driven by differences in daily temperature variability in different geographic regions or elevations. We find this interpretation confirmed in raw weather station observations. Higher elevation weather stations show greater temperature variance than low elevation stations in spring, and northern Alberta has a lower temperature variance than southern Alberta in spring (Table A.2).

3.2. Frost exposure changes under assisted migration

Data shown in Fig. 3 could in principle allow assessing risk of seed movement for assisted migration prescriptions. A point-to-point comparison of frost risks may, for example, be appropriate to evaluate changes from a source to target location for an endangered species in a conservation context. However, for practical purposes, transfer recommendations are often summarized into larger spatial units, such as ecosystem delineations or forestry seed zones. Because planting forest trees is usually organized around seed zone delineations, this is an obvious choice with practical benefits for this case study that could be used as a template elsewhere using other types of management delineations. In the following, we summarize frost risks shown in Fig. 3 for operational seed zones mapped in Fig. 1.

As a detailed example for a seed zone transfer, we evaluate lodgepole pine seeds originating from a southern, low elevation seed zone (NE low) to be moved to a more northern low elevation seed zone (PG low). The transfer represents an assisted migration

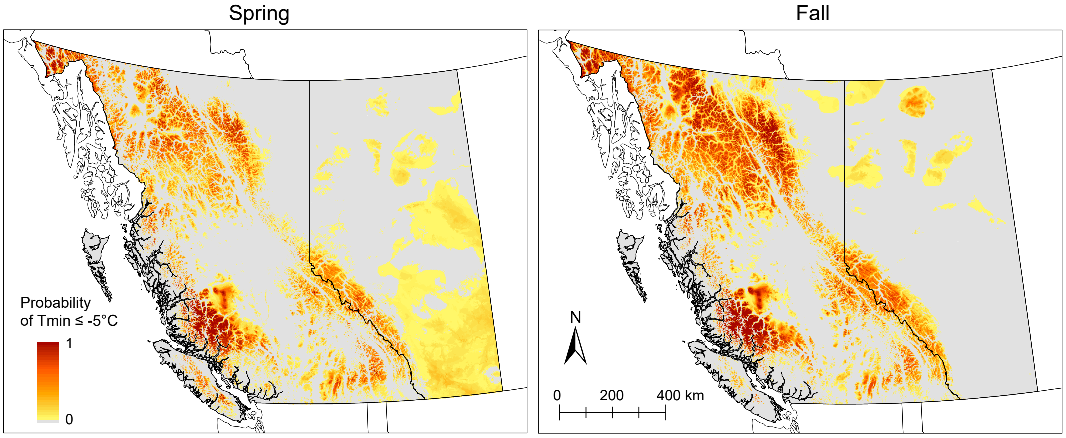

Fig. 3. Probability of experiencing a late spring frost or an early fall frost in any given year. Late spring frost events are defined as nights ≤ − 5 °C in a 30-day window following the day of year where growing degree days reach 100 (proxy for bud burst). Early fall frost events are nights ≤ − 5 °C in a 30-day window after the day with 9-hour night length (proxy for onset of dormancy).

prescription to an approximately 2 °C colder zone, about 300 km further north in British Columbia (Fig. 1). The frequency of daily coldest temperature values in the 30-day time intervals in spring and fall can be displayed as frost probability distributions for different seed zones (Fig. 4). Assuming no future climate warming and simply comparing two zones for the same 40-year data period, we can ask how spring and fall frost risks would change under this assisted migration prescriptions. We find that the risk of late spring frosts remains low. The southern low-elevation zone of lodgepole pine (NE low; Fig. 4 green solid line) has very low frost probabilities, as has the next zone to the north (PG low; Fig. 4 blue solid line) during the late-spring periods (Fig. 4, upper left panel). Similarly, fall frost risks for both low-elevation seed zones are close to zero (Fig. 4, upper right panel).

In contrast to latitudinal transfers, elevational transfers result in substantial changes to the probabilities of potentially damaging below-freezing events, when comparing low and high elevation zones in the same area. The probabilities of cold events (we highlight the area under the curve below –5 °C in Fig. 4) increases substantially both in spring and fall if seed sources are moved to higher elevation zone that is approximately 2 °C colder. Higher elevation seed zones have a wider range of freezing temperatures in both spring and fall, with wider distributions and lower peaks of the distributions. For example, the NE high seed zone (Fig. 4, green dashed line) has much higher frost risks than the low-elevation seed zone from the same region (Fig. 4, green solid line). With elevation, the probability of frost risk increases, as well as the occurrence of more extreme frosts (e.g., −10 °C or lower) in both spring and fall (Fig. 4, bottom row).

The minimum temperature distribution differences for latitude transfers also exist but are less obvious. Comparing low-elevation bands, northern seed zones have slightly less variation in cold events in spring and fall. For example, the more northern seed zone PG low has a narrower distribution with shorter tails, implying the same low risks of damaging cold events, despite generally colder climates with the distribution shifted to the left of the more southern NE low zone (Fig. 4, top row). In contrast, increased variability in cold events is a contributor to frost risks at high elevations (Fig. 4, bottom row). The probability distribution of the NE high seed zone is wider and has a lower maximum temperature in addition to being shifted to the left, compared to the generally warmer NE low zone. Both a downward shift in means and increased variance leads to considerably higher frost exposure at higher elevations in both the spring and fall 30-day windows that we evaluated.

3.3. Summary statistics for all potential seed transfers

To expand this analysis to all plausible transfers to adjacent seed zones at higher elevation or further north for all four species across British Columbia and Alberta, we report the changes in frost probabilities, represented by colored areas under the curve in Fig. 4 as numerical values in Table 1 and 2. The magnitude of changes in frost risks due to the possible 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 substantially in most cases when planting stock is moved to adjacent seed zones toward the north, while the average elevation remains constant or is slightly decreased (Table 1). In contrast, moving planting stock toward higher elevation, while the average latitude remains largely constant, 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 bud burst increases from 0.5% to 9.4% across all seed zones. The change for fall frosts as a consequence of elevation transfers is 16% (from an average 0.8% at lower seed zones to an average

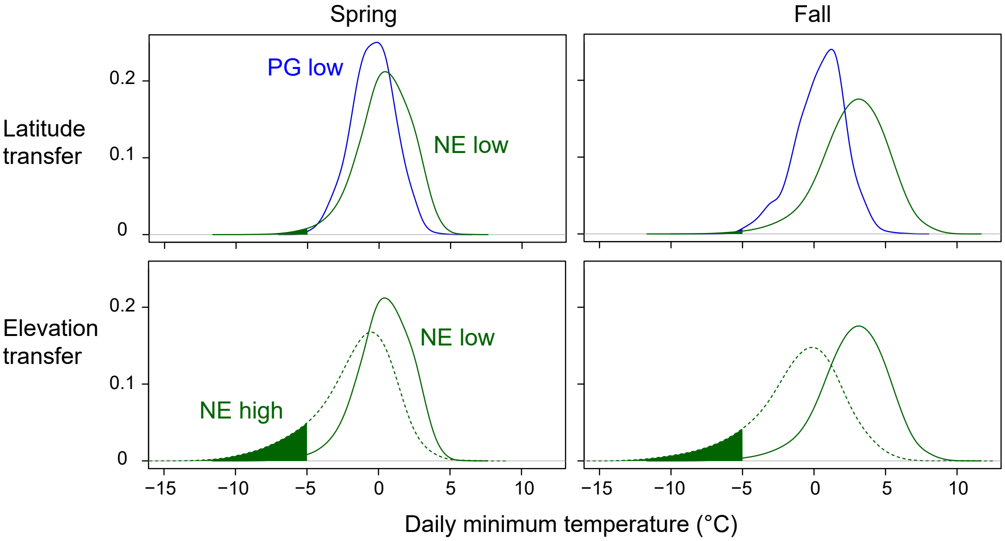

Fig. 4. Example of the probability distribution of the coldest late spring frost event (left panel) or the coldest early fall frost event (right panel) exceeding a threshold of ≤ -5 °C (highlighted by a colored area) for three lodgepole pine seed zones. The seed zone pairs represent a 350 km northward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

Table 1

Changes to frost risks with 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 bud break). Early fall frost events are nights ≤ − 5 °C in a 30-day window after the day of 9-hour night length (proxy for onset of dormancy). Examples provided for comparisons of movements among seed zones for 3 species.

Species Seed zone transfer	Transfer difference MAT (°C)	 Elev (m)	 Lat (km)	Spring risk change Probability (≤-5 °C)		Fall risk change Probability (≤-5 °C)	
Douglas-fir							
CT low to PG low	−1.2	−113	**+261**	0.1 to 0%	0%	0% to 1%	+1%
EK low to PG low	−1.2	−245	**+466**	0.1 to 0%	0%	0% to 1%	+1%
Lodgepole pine							
c to j	−2.8	−219	**+ 300**	0.2 to 0.7%	+1%	1% to 11%	+11%
EK low to CP low	−1.9	−252	**+ 580**	0.1 to 0.1%	+0%	0% to 2%	+2%
NE low to PG low	−1.2	−49	**+ 301**	0.7 to 0%	−1%	0% to 0%	0%
PG low to CP low	−1.4	−75	**+ 285**	0 to 0.1%	0%	0% to 2%	+2%
TO low to BV low	−2.8	−48	**+ 449**	0.7 to 0.2%	0%	0% to 1%	+1%
Interior spruce							
d to g2	−2.3	−149	**+ 269**	0.2 to 0.6%	0%	0% to 8%	+8%
d1 to e1	−1.5	−229	**+ 170**	1.2 to 2.4%	+1%	1% to 1%	0%
e to e1	−1	−129	**+ 149**	3.4 to 2.4%	−1%	1% to 1%	0%
e2 to d1	−1.3	−19	**+ 199**	3.4 to 1.2%	−2%	0% to 1%	+1%
g1 to g2	−2	−67	**+ 214**	0.5 to 0.6%	0%	0% to 8%	+8%
NE low to PG low	−1.8	−22	**+ 395**	0 to 0.1%	0%	0% to 1%	+1%
PG low to PR low	−2.5	−257	**+ 413**	0.1 to 0%	0%	1% to 4%	+3%
TO low to BV low	−1.8	−55	**+ 389**	2.2 to 0.6%	−2%	2% to 3%	0%
Average change	−1.9	−129	+ 323		0%		+3%

Table 2

Changes to frost risks for transfers upwards in elevation 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 bud break). Early fall frost events are nights ≤ − 5 °C in a 30-day window after the day of 9-hour night length (proxy for onset of dormancy). Examples of risk provided for movements among seed zones for 4 species.

Species Seed zone transfer	Transfer difference MAT (°C)	 Elev (m)	 Lat (km)	Spring risk change Probability (≤-5 °C)		Fall risk change Probability (≤-5 °C)	
Douglas-fir:							
M low to M high	−1.8	**+ 654**	+23	0.3 to 11%	+11%	0% to 1%	+1%
NE low to NE high	−2.1	**+ 547**	−25	0 to 3%	+3%	0% to 1%	+1%
Lodgepole pine:							
BV low to BV high	−1.1	**+ 359**	−3	0.2 to 14%	+13%	1% to 37%	+35%
CP low to CP high	−1.6	**+ 494**	+38	0.1 to 14%	+13%	2% to 46%	+44%
EK low to EK high	−2.7	**+ 631**	−1	0.1 to 1%	+1%	0% to 4%	+4%
NE low to NE high	−2.8	**+ 689**	−1	0.7 to 11%	+10%	0% to 7%	+7%
NS low to NS high	−2.7	**+ 752**	+4	1.1 to 22%	+21%	3% to 49%	+46%
PG low to PG high	−1.9	**+ 529**	−15	0 to 8%	+8%	0% to 18%	+18%
TO low to TO high	−2.4	**+ 617**	−10	0.7 to 7%	+6%	0% to 5%	+5%
Western larch:							
NE low to NE high	−2.5	**+ 638**	−23	1.1 to 10%	+9%	0% to 7%	+7%
Interior spruce:							
BV low to BV high	−1.2	**+ 431**	−23	0.6 to 8%	+7%	3% to 19%	+17%
NE low to NE high	−2.3	**+ 558**	+7	0 to 4%	+4%	0% to 2%	+2%
PG low to PG high	−1.4	**+ 492**	+20	0.1 to 2%	+2%	1% to 12%	+11%
TO low to TO high	−2.2	**+ 511**	−6	2.2 to 17%	+15%	2% to 24%	+21%
Average change	−2	**+ 564**	−1		+9%		+16%

17% at adjacent high elevation seed zones).

This general result that movement of seed to adjacent northern seed zones is less risky than movements to a higher elevation seed zone also holds true for earlier and more severe frost events in spring (–10 °C, and –15 °C following lower heat sum accumulation), and later and more severe frost events in fall (–8 °C, and –10 °C following longer critical night lengths). To see this pattern, compare the late spring frost risk changes highlighted with colors in Appendices Table A.3 for latitudinal transfers versus Table A.4 for elevation transfers. Large increases in frost risks are indicated by red colors. Similarly, for early fall frost risk changes, compare Appendices Table A.5 for latitudinal transfers versus Table A.6 for elevation transfers. Also for risks of early fall frosts, latitudinal transfers are preferable to elevation transfers.

The transfers that we evaluate in this study, both in elevation and in latitude are typically around 2 °C in mean annual temperature (last row in Tables 1 and 2). This 2 °C difference appears inherent in the design of Alberta's and British Columbia's seed zone system, and is the result of empirical research on what geographic seed transfer distances lead to loss of forest productivity and forest health.

We note that this value corresponds to a perceived “tipping point” where negative consequences of climate warming of more than 2 °C are anticipated for natural and managed ecological systems (IPCC, 2018). Assisted migration prescriptions to cooler environments by about 2 °C would therefore seem to be of an appropriate magnitude to make a difference in addressing negative impacts due to climate change. On average, such transfers would correspond to movements of planting stock of about 300–400 km northward given the approximately same elevation (Table 1, last row) or 500–600 m upward, given the same latitude, or a combination of both with an approximate conversion factor of a 100 m elevation change being equivalent to a 60 km latitude movement in Alberta and British Columbia.

It is important to note that the above generalizations for western Canada should be qualified for specific regions and species. Elevation movements in some areas have almost no changes to frost exposure as a consequence, for example, in the EK and NE seed zones of Douglas-fir in the southeast corner of British Columbia (Fig. 1, Table 2). The most pronounced increases in frost exposure are located in northwestern British Columbia for the BV, CP and NS seed zones (Fig. 1, Table 2). We did not make an attempt in this study to formally analyze the reasons for the variation in changes to frost risks associated with geographic movements. However, minimal changes to fall frost risks due to elevation transfers appear to be strongly associated with maritime climates of coastal rainforests (M seed zones) and interior rainforests represented by the NE, EK seed zones (Table 2 and Appendix Table A.6). Minimal changes to spring frost risk do not appear associated with maritime climates (Table 1, Appendix Table A.4). A logical next step would be a global analysis of the type we present here to generally quantify under which circumstances elevation transfers may not be associated with substantially increased frost risks, as was generally observed in this study.

3.4. *Response of planting stock to relocation and climate change*

Our analysis asks: if we move locally adapted planting stock to colder locations at higher elevations and latitudes in anticipation of future climate change that has not yet occurred, what are the changes to frost risk? However, climate has already warmed by about + 1.3 to + 1.5 °C since the beginning of the 20th century across the interior forests of Alberta and British Columbia, and by about + 0.8 °C for coastal forests of British Columbia. We can therefore assume that tree species and their populations already lag behind their optimal climate niche by a considerable amount today.

Responding to this climate warming signal, plants would break buds earlier due to reaching the heat sum requirement for dormancy release earlier as long as they have met their chilling requirement (Bailey and Harrington, 2006). There is good evidence that leaf unfolding and flowering dates of plants have advanced by up to a week in spring (e.g., Anderson et al., 2012; Schwartz and Reiter, 2000), but that may not necessarily cause changes to late spring frost risks when the temperature increase is primarily driven by increases in minimum temperature during periods of leaf unfolding (Bigler and Bugmann, 2018; Vitasse et al., 2018). Other research has found that under climate warming, earlier bud break timing could reduce the safety margin between the date of bud break and the date of the last spring frost event, and therefore potentially increase frost risks (e.g., Beaubien and Hamann, 2011; Bigler and Bugmann, 2018).

The situation may be more straight forward for the effect of climate warming on early fall frost exposure. Since bud set and the onset of dormancy in fall is primarily triggered by lengthening nights, which are not affected by climate change, it would imply that frost exposure distributions (such as those shown in Fig. 4) would be uniformly shifted to the right toward lower frost risks under climate warming. However, the beneficial effect of reduced frost risks due to a shift in distributions due to climate warming is relatively small, even when allowing for stronger local warming signals at higher elevation. For the example shown for fall frost risks distribution (Fig. 4, lower right panel) a 1.5 to 2.5 °C shift toward the right due to observed climate warming could not compensate for the increased exposure to frost risks due to movements to a higher elevation seed zones with higher daily temperature variability.

The empirical probability distributions developed for seed zones in this study suggest that changes to temperature variability could be key in determining future risks of frost exposure. However, future projections or historical evidence for changes in minimum temperature variability are not easy to obtain (e.g., Meehl et al., 2000; Zwiers et al., 2013). We also did not find any statistical evidence or even visual trends for changes in temperature variability within the 1980–2019 period, when plotting probability distributions of interpolated daily temperature data in the four consecutive decades of the 1980 s to 2010 s (data not shown).

Another consideration in assisted migration prescriptions is that populations are often locally adapted to a combination of biotic and abiotic factors. Local populations of tree species situated at high elevation or at far northern locations tend to evolve lower heat sum requirements leading to an earlier bud break relative to late spring frost risks, and similarly a later growth cessation relative to early fall frost risks. This leads to reduced safety margins against frost damage, but allows local populations to take full advantage of a short growing season in cold environments (Bigler and Bugmann, 2018; Dantec et al., 2015; Vitasse et al., 2018). Under more temperate conditions, the climate-phenology relationships can be reversed, with relatively longer growing season utilizations in common garden experiments observed in sources from warm, competitive environments (e.g., Mimura and Aitken, 2010). Also, populations from warmer southern locations tend to have lower levels cold hardiness (Sebastian-Azcona et al., 2019), more frost damage (Montwe et al., 2018), and respond less sensitively to shortening day length (e.g., Li et al., 2010; Liepe et al., 2016; Silvestro et al., 2019). Therefore, Silvestro et al. (2019) concluded that latitudinal transfer of southern, warm provenances northward would increase early fall frost risks relative to local populations should generally apply, except for the most northern and high elevation environments, where low safety margins have evolved to take advantage of a restricted growing season.

4. Conclusion

Compensating for observed and anticipated climate change may require movement of planting stock to colder environments further north or at higher elevation. At the same time, we must ensure that transferred planting stock does not suffer frost damage that would compromise their survival at the time of plantation establishment. The climatic risk analysis presented here suggests that transfers toward the north are preferable to transfers towards higher elevation, although this general observation does have some exceptions (e.g. transfers to higher elevation do not appear associated with increased fall frost risks under maritime climate conditions). For northward transfers of approximately 300–400 km, there are virtually no changes to late spring and early fall frost risks compared to the status quo of not moving seed sources. In contrast, an approximately 500–600 m transfer to higher elevation was associated with a substantial increase in frost risks. The reason for the observed latitudinal and altitudinal changes in spring frost risks is the increased variability in daily temperatures. Temperature variability (and associated frost risks) increases with elevation but not with latitude. Assuming a temperature-controlled day of bud burst, late spring frost risks of northwards transfers should remain near identical to historic probabilities. Assuming a day-length controlled onset of dormancy and climate warms as projected, early fall frost risks may decrease overall compared to historical probabilities for northward transfers but not under transfers to higher elevation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100380.

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Appendix A

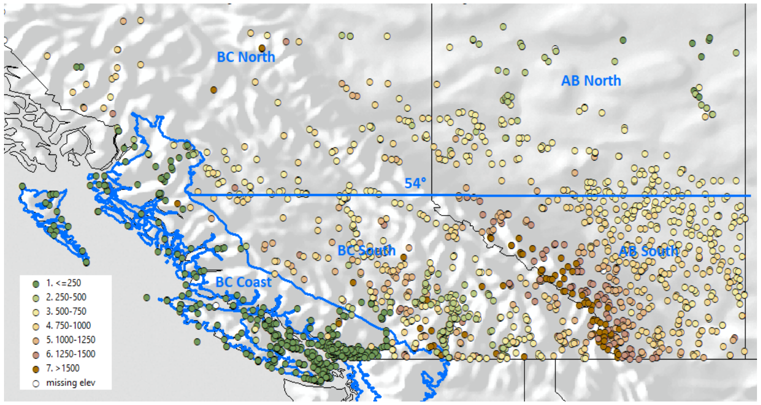
Appendix A.1. R code to estimate the probability of late spring frosts after bud break, and early fall frosts before onset of dormancy. The code process files downloaded with the Daymet Single Pixel Extraction Web Service API (*https://daymet.ornl.gov/web_services*).

```
library(data.table)
d <- fread('daymet.csv', skip=6,
           col.names=c('yr','doy','dl','pre','srad','swe','tx','tn','vp'))
head(d)

# Daymet variables used below
# yr  = year
# doy = day of year
# dl  = day length (seconds)
# tx  = daily maximum temperature (degree C)
# tn  = daily minimum temperature (degree C)


# Estimate probabilities of late spring frost events
b   <- 5   # set base temperature (b) for growing degree day calculation here
hsr <- 100 # set heat sum requirement (hsr) for budbreak here
spl <- 30  # set spring period length (spl) for late spring frost screening
sft <- -5  # set spring frost threshold (sft) here

s <- d[, t := (tn + tx)/2]                 # daily average temperature (t) calculation
s <- s[, gdd := ifelse(t >= b, t-b, 0)]    # growing degree day (gdd) calculation
s <- s[, hs := cumsum(gdd), keyby = yr]    # heatsum (hs) calculation
s <- s[hs>=hsr, head(.SD,spl), keyby = yr] # retain data for period following bud break
s[,.(prob_lsf = mean(min < sft))]          # probability of a late spring frost < sft


# Estimate probabilities of early fall frost events
dlt <- 15  # set day length threshold (dlt) to represent estimated onset of dormancy
fpl <- 30  # set fall period length (spl) for early fall frost screening
fft <- -5  # set fall frost threshold (fft) here

eod <- d[(doy > 180), which.min(abs(dl - dlt*60*60)) + 180]  # estimated onset of dormancy
f <- d[doy %between% c(eod, eod+fpl-1)]   # retain data for period after onset of dormancy
# f <- f[, .(min = min(tn)), by = yr]       # retain coldest early fall frost in each year
f[,.(prob_eff = mean(min < fft ))]        # probability of an early fall frost < fft
```

Appendix A.2. Variability in daily weather station data expressed in standard deviations of daily minimum temperature within a month (green = low variability, red = high variability). The reference map below the table shows the regions and elevation bands within the Canadian provinces of British Columbia (BC) and Alberta (AB) evaluated here.

Region & Elev	Month			Spring					Fall				No of Stations
BC South	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	
<=250	7.1	5.6	3.9	3.2	3.1	2.9	2.8	2.8	3.4	3.8	5.2	5.8	12
250-500	7.5	6.3	4.4	3.7	3.7	3.4	3.4	3.4	3.8	4	4.9	6.2	122
500-750	8.6	7.1	5.1	3.8	3.8	3.4	3.3	3.5	4	4.2	5.7	7.4	124
750-1000	9.3	7.9	6	3.8	3.8	3.6	3.4	3.6	4	4.4	6.4	8.1	90
1000-1250	8.8	7.7	6.1	4	3.8	3.7	3.7	3.7	4.1	4.4	6.5	7.8	78
1250-1500	8.3	7.1	5.9	4	3.1	3.2	3.1	3.2	3.6	4.1	6.5	7.3	15
>1500	7.5	6.5	5.5	4.4	3.8	3.8	3.8	4	4.3	4.8	6.2	6.9	19
BC North													
<=250	8.0	7	4.9	3	3	2.8	2.4	2.8	3.1	3.6	5.3	7.1	10
250-500	11.2	10	8.4	4.9	3.7	3.4	3	3.2	3.8	5.2	8.7	11	9
500-750	11.1	9.8	8	4.5	3.8	3.5	3.2	3.6	4	4.8	7.9	9.8	69
750-1000	11.0	9.7	8.2	5	3.6	3.4	3.1	3.5	3.9	5	8.3	10	39
1000-1250	10.3	9.9	7.9	5.7	3.5	3.2	2.9	3.7	4.1	5.2	8.6	10	9
BC Coast													
<=250	5.0	4.1	3.2	2.9	2.9	2.6	2.4	2.5	2.9	3.3	3.9	4.4	422
250-500	8.7	7.1	4.8	3.6	3.7	3.4	3.1	3.4	4.1	4.2	5.6	7.4	20
500-750	7.9	6.6	4.4	3.1	3.1	2.9	2.8	2.9	3.6	3.9	4.8	6.4	13
750-1000	7.6	6.9	5.3	3.6	3.4	3.5	3.3	3.2	3.6	3.8	5.3	6.6	7
AB South													
500-750	10.1	9.3	8.4	5.2	4.3	3.5	3.2	3.6	4.1	5	7.4	9.2	155
750-1000	10.2	9.3	8.1	5	4.1	3.5	3.3	3.6	4.2	5.2	7.5	9.3	187
1000-1250	10.5	9.2	7.8	5	4	3.5	3.3	3.5	4.2	5.4	7.7	9.4	85
1250-1500	10.8	9.4	8.2	5.4	4	3.7	3.5	3.7	4.3	5.7	7.9	9.7	75
>1500	9.8	8.1	7.7	5	3.9	3.4	3.7	3.9	4.1	5.3	7.6	8.9	52
AB North													
<=250	9.5	9.5	9.6	7.7	5.2	4.3	3.7	4.3	4.5	5.3	8.4	9.3	7
250-500	10.4	10	9.6	6.6	4.5	3.8	3.4	3.9	4.4	5.4	8.6	9.8	40
500-750	10.7	9.9	8.8	5.5	4.2	3.5	3.2	3.6	4.2	5.1	8	9.7	140
750-1000	11.0	9.4	8.3	5	4.1	3.3	3.3	3.6	4	5	7.5	9.8	14
1000-1250	9.7	9.2	7.7	5.3	4.1	3.3	3.1	3.7	3.9	5.1	7	9.1	5

Reference map for weather stations by region and elevation band



Appendix A.3. Sensitivity analysis for late spring frost events for assisted migration towards the north. Source DoY and target DoY are the days of the year where critical heat sums are met. The changes in probabilities of late spring frost risks due to the seed transfer are highlighted by a color scheme that is consistently applied across Appendix A.3 and A.4 for direct comparison of elevation versus latitude transfers. Examples of risk comparisons among seed zones for 4 species are exhibited in the table (Df: Douglas-fir; Lp: lodgepole pine; Wl: western larch; Is: Interior spruce).

		Degree days above 5 °C								Degree days above 0 °C							
		Risk of -5 °C after 100 degree days				Risk of -10 °C after 20 degree days				Risk of -10 °C after 70 degree days				Risk of -15 °C after 40 degree days			
Spec.	Seed zone transfer	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.
Df	CT low to PG low	144	148	0% to 0%	0%	118	127	1% to 0%	-1%	96	107	12% to 7%	-5%	83	96	9% to 6%	-3%
Df	EK low to PG low	137	148	0% to 0%	0%	113	127	1% to 0%	-1%	92	107	9% to 7%	-2%	80	96	8% to 6%	-2%
Lp	c to j	143	146	0% to 1%	+1%	120	125	3% to 0%	-2%	107	116	11% to 4%	-7%	96	108	16% to 3%	-13%
Lp	EK low to CP low	139	149	0% to 0%	0%	114	129	1% to 0%	-1%	93	111	9% to 5%	-3%	82	100	7% to 5%	-2%
Lp	NE low to PG low	140	143	1% to 0%	-1%	116	119	0% to 1%	0%	96	97	1% to 10%	+9%	85	85	1% to 8%	+7%
Lp	PG low to CP low	143	149	0% to 0%	0%	119	129	1% to 0%	0%	97	111	10% to 5%	-5%	85	100	8% to 5%	-3%
Lp	TO low to BV low	140	154	1% to 0%	0%	113	132	0% to 0%	0%	91	111	8% to 4%	-4%	78	100	5% to 2%	-3%
Is	d to g2	140	144	0% to 1%	0%	118	123	3% to 0%	-2%	104	114	12% to 4%	-8%	93	106	17% to 4%	-14%
Is	d1 to e1	139	143	1% to 2%	+1%	118	122	3% to 1%	-1%	107	115	10% to 6%	-4%	98	108	9% to 4%	-5%
Is	e to e1	140	143	3% to 2%	-1%	119	122	0% to 1%	+1%	110	115	4% to 6%	+2%	102	108	11% to 4%	-7%
Is	e2 to d1	135	139	3% to 1%	-1%	113	118	3% to 1%	-2%	104	107	11% to 10%	-1%	95	98	15% to 9%	-5%
Is	g1 to g2	139	144	1% to 1%	0%	116	123	4% to 0%	-4%	103	114	15% to 4%	-11%	92	106	18% to 4%	-15%
Is	NE low to PG low	130	147	0% to 0%	0%	106	125	0% to 0%	0%	83	105	2% to 8%	+6%	72	93	2% to 6%	+4%
Is	PG low to PR low	147	145	0% to 0%	0%	125	125	0% to 1%	0%	105	116	8% to 5%	-3%	93	108	6% to 5%	-2%
Is	TO low to BV low	145	157	2% to 1%	-2%	119	134	0% to 0%	0%	97	114	11% to 2%	-9%	85	102	6% to 1%	-4%
Average		**140**	**147**		**0%**	**116**	**125**		**-1%**	**99**	**111**		**-3%**	**88**	**101**		**-4%**

Appendix A.4. Sensitivity analysis for late spring frost events for assisted migration towards higher elevations. Source DoY and target DoY are the days of the year where critical heat sums occur. The changes in probabilities of late spring frost risks due to the seed transfer are highlighted by a color scheme that is consistently applied across Appendix A.3 and A.4 for direct comparison of elevation versus latitude transfers. Examples of risk comparisons among seed zones for 4 species are exhibited in the table (Df: Douglas-fir; Lp: lodgepole pine; Wl: western larch; Is: Interior spruce).

		Degree days above 5 °C								Degree days above 0 °C							
		Risk of -5 °C after 100 degree days				Risk of -10 °C after 20 degree days				Risk of -10 °C after 70 degree days				Risk of -15 °C after 40 degree days			
Spec.	Seed zone transfer	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.
Df	M low to M high	113	148	0% to 11%	+11%	67	115	1% to 7%	+6%	32	81	7% to 25%	+18%	21	63	1% to 6%	+5%
Df	NE low to NE high	128	146	0% to 3%	+3%	104	121	0% to 1%	+1%	82	103	2% to 4%	+2%	70	93	2% to 1%	-2%
Lp	BV low to BV high	154	181	0% to 14%	+13%	132	151	0% to 3%	+3%	111	137	4% to 8%	+5%	100	126	2% to 2%	0%
Lp	CP low to CP high	149	173	0% to 13%	+13%	129	146	0% to 4%	+4%	111	134	5% to 9%	+3%	100	124	5% to 3%	-2%
Lp	EK low to EK high	139	164	0% to 1%	+1%	114	136	1% to 0%	0%	93	121	9% to 6%	-3%	82	110	7% to 3%	-4%
Lp	NE low to NE high	140	162	1% to 11%	+10%	116	132	1% to 11%	+10%	96	119	1% to 11%	+10%	85	108	1% to 1%	0%
Lp	NS low to NS high	156	177	1% to 21%	+20%	133	148	0% to 10%	+10%	112	133	2% to 21%	+19%	100	120	1% to 4%	+3%
Lp	PG low to PG high	143	171	0% to 8%	+8%	119	143	1% to 1%	+1%	97	127	10% to 7%	-3%	85	115	8% to 6%	-2%
Lp	TO low to TO high	140	161	1% to 7%	+6%	113	132	0% to 1%	+1%	91	115	8% to 8%	+1%	75	102	5% to 2%	-2%
Wl	NE low to NE high	137	153	1% to 10%	+9%	112	126	0% to 2%	+2%	92	110	2% to 8%	+6%	81	99	1% to 1%	0%
Is	BV low to BV high	157	175	1% to 7%	+7%	134	146	0% to 2%	+2%	114	131	2% to 4%	+2%	102	120	1% to 2%	+1%
Is	NE low to NE high	130	155	0% to 4%	+4%	106	129	0% to 1%	+1%	83	114	2% to 4%	+3%	72	103	2% to 0%	-2%
Is	PG low to PG high	147	163	0% to 2%	+2%	125	138	0% to 0%	0%	105	123	8% to 4%	-4%	93	112	6% to 4%	-2%
Is	TO low to TO high	145	166	2% to 17%	+15%	119	137	0% to 3%	+3%	97	120	11% to 14%	+3%	85	107	6% to 4%	-2%
Average		**141**	**164**		**+9%**	**116**	**136**		**+3%**	**94**	**119**		**+4%**	**82**	**107**		**-1%**

Appendix A.5. Sensitivity analysis for early fall frost events for assisted migration towards the north. Source DoY and target DoY are the days of the year where critical photoperiods occur. The changes in probabilities of early fall frost risks due to the seed transfer are highlighted by a color scheme that is consistently applied across Appendix A.5 and A.6 for direct comparison of elevation versus latitude transfers. Examples of risk comparisons among seed zones for 4 species are exhibited in the table (Df: Douglas-fir; Lp: lodgepole pine; Wl: western larch; Is: Interior spruce).

		Risk of -5 °C after 9-hour night length				Risk of -8 °C after 10-hour night length				Risk of -10 °C after 11-hour night length			
Spec.	Seed zone transfer	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.
Df	CT low to PG low	218	222	0% to 1%	+1%	234	236	0% to 1%	0%	249	251	2% to 1%	-1%
Df	EK low to PG low	214	222	0% to 1%	+1%	231	236	0% to 1%	+1%	248	251	0% to 1%	+1%
Lp	c to j	223	227	1% to 11%	+11%	236	239	0% to 7%	+7%	251	252	1% to 13%	+12%
Lp	EK low to CP low	214	224	0% to 2%	+2%	231	237	0% to 1%	+1%	248	251	0% to 1%	+1%
Lp	NE low to PG low	214	219	0% to 0%	0%	231	234	0% to 0%	0%	248	250	0% to 2%	+2%
Lp	PG low to CP low	219	224	0% to 2%	+2%	234	237	0% to 1%	+1%	250	251	2% to 1%	-1%
Lp	TO low to BV low	214	222	0% to 1%	+1%	231	236	0% to 1%	+1%	248	250	1% to 1%	0%
Is	d to g2	223	227	0% to 8%	+8%	236	239	0% to 5%	+5%	251	252	1% to 10%	+8%
Is	d1 to e1	225	227	1% to 1%	0%	238	239	1% to 2%	+1%	251	252	4% to 4%	0%
Is	e to e1	225	227	1% to 1%	0%	238	239	1% to 2%	+1%	251	252	5% to 4%	-2%
Is	e2 to d1	222	225	0% to 1%	+1%	236	238	1% to 1%	0%	250	251	3% to 4%	0%
Is	g1 to g2	224	227	0% to 8%	+8%	237	239	0% to 5%	+5%	251	252	3% to 10%	+6%
Is	NE low to PG low	215	222	0% to 1%	+1%	232	236	0% to 1%	+1%	249	250	0% to 2%	+2%
Is	PG low to PR low	222	229	1% to 4%	+3%	236	241	1% to 2%	+1%	250	253	2% to 4%	+2%
Is	TO low to BV low	216	223	2% to 3%	0%	233	236	2% to 1%	0%	249	251	4% to 1%	-3%
Average		**219**	**224**		**+3%**	**234**	**237**		**+2%**	**250**	**251**		**+2%**

Appendix A.6. Sensitivity analysis for early fall frost events for assisted migration towards higher elevations. Source DoY and target DoY are the days of the year where critical photoperiods occur. The changes in probabilities of early fall frost risks due to the seed transfer are highlighted by a color scheme that is consistently applied across Appendix A.5 and A.6 for direct comparison of elevation versus latitude transfers. Examples of risk comparisons among seed zones for 4 species are exhibited in the table (Df: Douglas-fir; Lp: lodgepole pine; Wl: western larch; Is: Interior spruce).

		Risk of -5 °C after 9-hour night length				Risk of -8 °C after 10-hour night length				Risk of -10 °C after 11-hour night length			
Spec.	Seed zone transfer	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.	Source DoY	Target DoY	Change in probability	Prob. Diff.
Df	M low to M high	213	214	0% to 1%	+1%	231	231	0% to 0%	0%	248	248	0% to 1%	+1%
Df	NE low to NE high	214	214	0% to 1%	+1%	231	231	0% to 1%	+1%	248	248	0% to 2%	+2%
Lp	BV low to BV high	222	223	1% to 37%	+35%	236	237	1% to 22%	+21%	250	251	1% to 21%	+20%
Lp	CP low to CP high	224	225	2% to 46%	+44%	237	238	1% to 30%	+29%	251	251	1% to 31%	+30%
Lp	EK low to EK high	214	214	0% to 4%	+4%	231	231	0% to 1%	+1%	248	248	0% to 7%	+7%
Lp	NE low to NE high	214	214	0% to 7%	+7%	231	231	0% to 7%	+7%	248	248	0% to 8%	+8%
Lp	NS low to NS high	225	225	3% to 49%	+46%	238	238	1% to 29%	+28%	251	251	1% to 24%	+24%
Lp	PG low to PG high	219	219	0% to 18%	+18%	234	234	0% to 12%	+12%	250	250	2% to 17%	+15%
Lp	TO low to TO high	214	214	0% to 5%	+5%	231	231	0% to 4%	+4%	248	248	1% to 7%	+6%
Wl	NE low to NE high	213	213	0% to 7%	+7%	231	231	0% to 6%	+5%	248	248	1% to 9%	+8%
Is	BV low to BV high	223	222	3% to 19%	+17%	236	236	1% to 11%	+10%	251	251	1% to 11%	+10%
Is	NE low to NE high	215	215	0% to 2%	+2%	232	232	0% to 2%	+2%	249	249	0% to 4%	+4%
Is	PG low to PG high	222	222	1% to 12%	+11%	236	236	1% to 8%	+8%	250	250	2% to 11%	+10%
Is	TO low to TO high	216	216	2% to 24%	+21%	232	232	2% to 18%	+16%	249	249	4% to 23%	+19%
Average		**218**	**218**		**+16%**	**233**	**234**		**+10%**	**249**	**249**		**+12%**