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A Proposed Climate-based Seed Transfer System for British Columbia

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Greg O'Neill, Tongli Wang, Nicholas Ukrainetz, Lee Charleson, Leslie McAuley, Alvin Yanchuk, and Susan Zedel

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Prepared by

Greg O'Neill
B.C. Ministry of Forests, Lands
and Natural Resource Operations
Tree Improvement Branch
Vernon, B.C.

Tongli Wang
University of British Columbia
Department of Forest and Conservation Sciences
Vancouver, B.C.

Nicholas Ukrainetz
B.C. Ministry of Forests, Lands
and Natural Resource Operations
Tree Improvement Branch
Surrey, B.C.

Lee Charleson
Alberta Ministry of Economic
Development and Trade
Alberta Tree Improvement Centre
and Seed Centre
Smokey Lake, Alta.

Leslie McAuley, Alvin Yanchuk, and
Susan Zedel
B.C. Ministry of Forests, Lands
and Natural Resource Operations
Tree Improvement Branch
Victoria, B.C.

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ABSTRACT

A well-designed seedlot selection system is central to the maintenance of healthy and productive forest plantations, particularly in an era of rapidly changing climates. Opportunities for improving the effectiveness and efficiency of seedlot selection in British Columbia are provided by new technologies, analysis techniques, and genetic data. We propose a climate-based system of seed transfer that is expected to better match seedlots to planting sites using new transfer functions to identify biogeoclimatic ecosystem classification units where each seedlot is anticipated to grow well. The system also: (1) facilitates the use of assisted migration to reduce climate change impacts to forest health and productivity; (2) allows for wider seedlot deployability; (3) increases ease of use; (4) simplifies system updating; (5) quantifies adaptation of seed source options to improve seed source deployment; and (6) integrates with species selection.

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1 INTRODUCTION

A well-designed seedlot selection system is central to the maintenance of healthy and productive forest plantations, particularly in an era of rapidly changing climates. Opportunities for improving the effectiveness and efficiency of seedlot selection in British Columbia are provided by new technologies, analysis techniques, and genetic data. We propose shifting from a system of seed transfer based primarily on geography to one based on climate, to better match seedlots to planting sites. Using a comprehensive set of provenance data, site-specific climate-based transfer functions are used to identify biogeoclimatic ecosystem classification (BEC) units where each seedlot is anticipated to grow well. The system also: (1) facilitates the use of assisted migration to reduce climate change impacts to forest health and productivity; (2) allows for wider seedlot deployability; (3) increases ease of use; (4) simplifies system updating; (5) quantifies adaptation of seed source options to improve seed source deployment; and (6) integrates with species selection.

2 BACKGROUND

Selecting the right seedlot for a plantation's climate is crucially important for maintaining forest health and productivity. According to White et al. (2007): "Choosing appropriate species and [seed] sources is the single most important genetic decision in a plantation program." Furthermore: "The largest, cheapest and fastest gains in most forest tree improvement programs can be made by ensuring the use of the proper species and seed sources within the species" (Zobel and Talbert 1984). In this era of a rapidly changing climate, matching seedlots to plantation climate becomes even more critical and challenging.

Wise seedlot selection, in conjunction with assisted migration, is widely regarded as playing a central role in addressing this challenge (Leech et al. 2011; Pedlar et al. 2012; Rehfeldt et al. 2014a). Consequently, the Tree Improvement Branch of the B.C. Ministry of Forests, Lands and Natural Resource Operations and the Forest Genetics Council of British Columbia have identified as a priority the development of a new seed transfer system based directly on climate that will facilitate the use of assisted migration to mitigate climate change impacts (Forest Genetics Council of British Columbia 2009; B.C. Ministry of Forests, Lands and Natural Resource Operations 2014).

The Climate-based Seed Transfer project (CBST)[1] was initiated in 2012 to modernize the province's seedlot selection system and facilitate wider use of assisted migration to help maintain forest health and productivity in a changing climate (B.C. Ministry of Forests, Lands and Natural Resource Operations 2012). The scope of the project includes all forest tree species and seed genetic classes (i.e., Class A: orchard; Class B: natural stand; and Class B+: natural stand superior provenance) governed under the Chief Forester's *Standards for Seed Use* (Snetsinger 2004).[2]

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[1] For further details, see: www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/tree-seed/seed-planning-use/climate-based-seed-transfer.

[2] See: www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/tree-seed/legislation-standards/chief-forester-s-standards-for-seed-use.

This report summarizes work conducted during Phase 1 (Science Foundation) of the CBST project, thus allowing clients and stakeholders an opportunity to provide feedback on the proposed system. This summary also serves to document the process and recommendations made during Phase 1 to facilitate future revisions to the province's seed transfer system. Subsequent project phases will involve policy development, implementation, and monitoring and revisions.

3 WHAT IS SEED TRANSFER?

In the 1800s, foresters in Europe noted that plantations grew poorly when they were established with seed sources originating from climates that differed greatly from that of the plantation (Langlet 1971). Provenance tests and observations by foresters in the 1900s confirmed the "local is best" adage (Bates 1930; Raymond and Lindgren 1990; Wu and Ying 2004; Savolainen et al. 2007), notwithstanding some exceptions (Namkoong 1969), and led to the first restrictions on tree seed transfer (Lindquist 1948; Zobel and Talbert 1984; Ying and Yanchuk 2006).

Informed systems for constraining seedlot selection (a.k.a. seed transfer) are fundamental to forestry operations, particularly in climatically complex environments. Natural selection during the postglacial and pre-industrial eras has moulded tree populations such that population variation in many species is patterned strongly on climate (Lu et al. 2014), but also is related to photoperiod and distributions of pests, fires, soils, and soil biota (Foy 1988; Lester et al. 1990; Aitken et al. 2008; Kranabetter et al. 2012).

Maladaptation of forest trees may arise when seedlings are planted outside the environments in which they have undergone natural selection most recently, and can significantly increase the probability of stem-form defects and reduced growth (Campbell 1979; Zobel and Talbert 1984; O'Neill et al. 2014). Therefore, guidelines that are too permissive can result in compromised health, productivity, and economic value of planted forests (Zobel and Talbert 1984), whereas guidelines that are too stringent can lead to excessive natural stand seed collection efforts or unwarranted numbers of breeding and seed production programs, adding significant cost to forestry activities (Crowe and Parker 2005).

3.1 Constraining Seed Transfer Helps Ensure Plantation Health and Productivity

The primary goal of a seed transfer system is to achieve healthy and productive forests by ensuring that plantations are regenerated with seed that is well adapted to the plantation environment. To obtain effective matching of seed with plantations, jurisdictions are divided into zones that are climatically, geographically, or genetically (adaptively) uniform (Parker and van Niejenhuis 1996; Parker 2000; St. Clair et al. 2005; Hamann et al. 2011; Ukrainetz et al. 2011). Seed source movement is then restricted to its zone of origin (fixed zones) or to prescribed climatic, geographic, or adaptive transfer limits from its point of origin (focal point zones). Approaches have also been developed to delineate zones in a way that limits genotype–environment interaction (Roberds and Namkoong 1989; Hamann et al. 2000), that optimizes zone delineation such that the proportion of a jurisdiction covered by a given number of zones is maximized (Crowe and Parker 2005), or that minimizes total maladaptation across all zones (O'Neill and Aitken 2004).

3.2 Seed Transfer Systems

Two types of seed transfer systems are recognized: (1) *fixed zone systems*, in which a jurisdiction is divided into a relatively small number of large zones between which seed transfer is not permitted, and (2) *focal point systems*, in which transfer limits identify a unique deployment zone around every seed source (or a unique procurement zone around every plantation) (Parker and van Niejenhuis 1996) (see Figure 1a and 1b). Zones in both systems are relatively uniform in geography, climate, ecology, or genetic adaptation.

Fixed zone systems are simpler and more common than focal point systems; however, the ability to deploy seed is constrained because seed sources located near a fixed zone boundary may not be deployed across the boundary, despite being well adapted to some locations in the neighbouring seed zone. Ukrainetz et al. (2011) found that, for a given maximum allowable transfer distance, seed could be deployed to 1.5–4.0 times more area with a focal point system than with a fixed zone system, increasing seedlot selection options and providing greater flexibility for seed users. Focal point systems, which allow seed to be deployed maximally (i.e., to the transfer limit) around each focal point, are gaining popularity because advances in geographic interfacing software are simplifying the delineation of deployment and procurement zones.

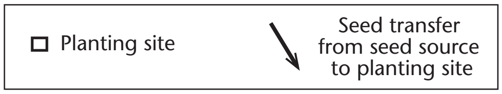
Ukrainetz et al. (2011) proposed a third system that divides a jurisdiction into a large number of small fixed zones (see Figure 1c). Seed transfer is permitted into zones with a similar geography, climate, ecology, or genetic adaptation to that of the seed source zone, thereby capitalizing on the simplicity of fixed zones while achieving a level of deployment approaching that of focal point systems. We call this a "focal zone" system because deployment remains centred on the seed origin or plantation location (i.e., the "focus"); however, the focus is a zone, as opposed to a point.

3.3 Zone Delineation Variable

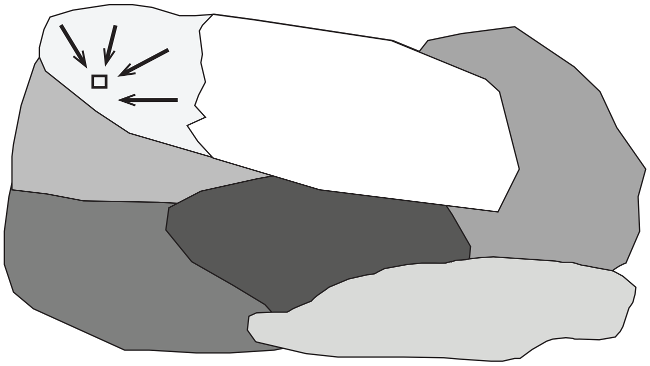
Seed transfer zones, regardless of the system for which they were generated (fixed, focal point, or focal zone), are delineated along geographic, ecosystem, climate, or genetic (adaptation) boundaries or contours. Maladaptation risk increases with genetic transfer distance (Campbell 1986); therefore, zone delineations are sought that minimize the adaptive genetic variation (and therefore minimize the average adaptive transfer distance) among populations within seed zones (O'Neill and Aitken 2004). However, accurate maps of genetic adaptation are difficult or impossible to develop for some species or regions because of insufficient population sampling in provenance trials. In these situations, or where provenance data are unavailable, jurisdictions are often divided into zones that are uniform in geography, climate, or ecology, with these variables acting as a surrogate for genetic adaptation.

3.4 Critical Seed Transfer Distance

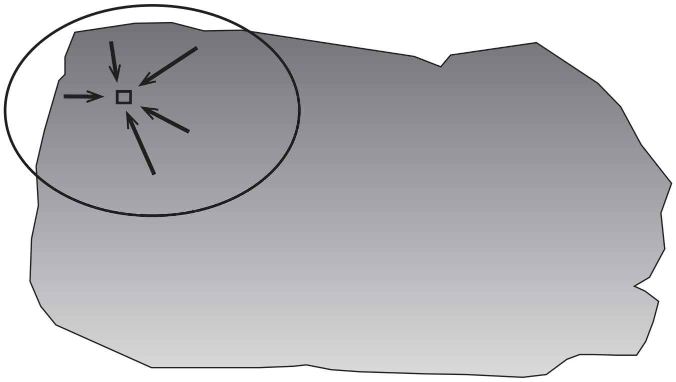
The maximum distance seed can be moved safely without incurring unacceptable levels of maladaptation is called the "critical seed transfer distance" (Ukrainetz et al. 2011). This distance is a key feature of all seed transfer systems because it is used to guide the size of fixed seed zones, the magnitude of seed transfer limits that define the size of focal point seed zones, and the number of zones that seed from a given focal zone can be deployed to in a



(a) Fixed zone seed transfer system



(b) Focal point seed transfer system



(c) Focal zone seed transfer system

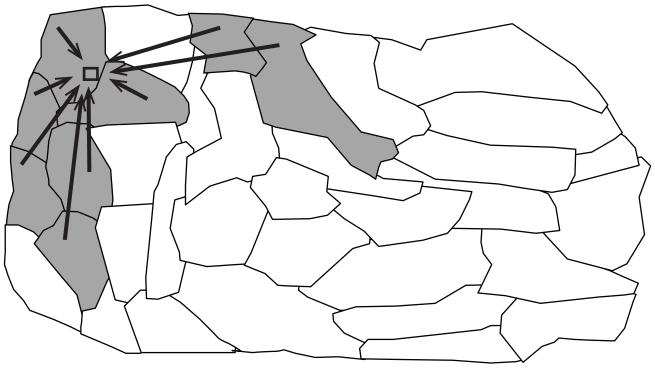


FIGURE 1 *Examples of (a) fixed zone, (b) focal point, and (c) focal zone seed transfer systems. In fixed zone systems, seed may not be moved across zone boundaries, despite the proximity of seed source to the boundary. In focal point systems, the zone boundary is centred on the focal point. In focal zone systems, seed can be moved to all zones that are climatically similar to the focal zone.*

focal zone system. Critical seed transfer distances are often interpreted from transfer functions that use provenance data to relate population transfer distance (usually in terms of climate, geography, or genetic adaptation) with population growth or health (Raymond and Lindgren 1990; see examples in Figure 2).

To calculate critical seed transfer distance, we selected the "transfer function" approach over the risk index (Campbell 1986) and least significant difference (Rehfeldt 1994) approaches, because this approach estimates phenotypic impacts for a given transfer distance.[3] The development of new approaches that examine genetic variation within and among populations in adaptively important portions of their genome aim to complement existing phenotypic field-based provenance or family test approaches to quantifying critical seed transfer distances.[4]

3.5 Examples of Seed Transfer Systems

Although constraints on seed deployment through seed zones were recommended as early as 1930 in the United States (Bates 1930), it was not until 1966 that state governments initiated forest tree seed certification and a system of fixed seed zones in the Pacific Northwest (Johnson et al. 2004). In British Columbia, the first seed zones were drafted in the 1940s for Vancouver Island (B.C. Forest Service 1946; Ying and Yanchuk 2006) and re-drafted in 1962 to include the interior of British Columbia; however, regulation of seed movement began only in 1987 with the creation of fixed seed planning zones, together with geographic transfer limits as described in the *Seed and Vegetative Material Guidebook* under the authority of the *Forest Practices Code of British Columbia Act* and its Timber Harvesting and Silviculture Practices Regulation (B.C. Ministry of Forests 1995; Ying and Yanchuk 2006).[5] Delineation of these early zones was made primarily on the basis of field observations by Research Branch geneticists and, where data were available, by univariate regression models relating provenance geographic variables to provenance growth.

Transfer of natural stand seed sources (Genetic Class B) in British Columbia is currently constrained using 24 fixed seed planning zones that apply to all species. Transfer is further constrained by way of a focal point system that uses species-specific and planning zone–specific geographic (latitude, longitude, and elevation) transfer limits (Snetsinger 2004). For example, within the Submaritime Seed Planning Zone, interior lodgepole pine may be moved a maximum of 2° north, 1° south, 3° west, 2° east, 500 m upward, and 100 m downward. A caveat allows seed of most species to be used outside its zone of origin, as long as it remains within its biogeoclimatic zone of origin, and within the transfer limits for the species and seed planning zone.

Transfer of orchard seed (Genetic Class A) is constrained using fixed, species-specific seed planning zones that are further divided into elevation bands called "seed planning units." For example, the lodgepole pine Thompson-Okanagan Seed Planning Zone is divided into two planning units: (1) low (0 to 700–1400 m), and (2) high (700 to 1400–1600 m). Seed generated in the lodgepole pine Thompson-Okanagan' "low" orchard are from parents that originate primarily from that planning unit and can be deployed only within the unit.

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[3] For a more detailed rationale, see Ukrainetz et al. (2011).

[4] Projects such as AdapTree (http://adaptree.forestry.ubc.ca/) are using this approach.

[5] See also British Columbia's seed transfer history: www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/tree-seed/seed-planning-use/seed-planning-chronology.

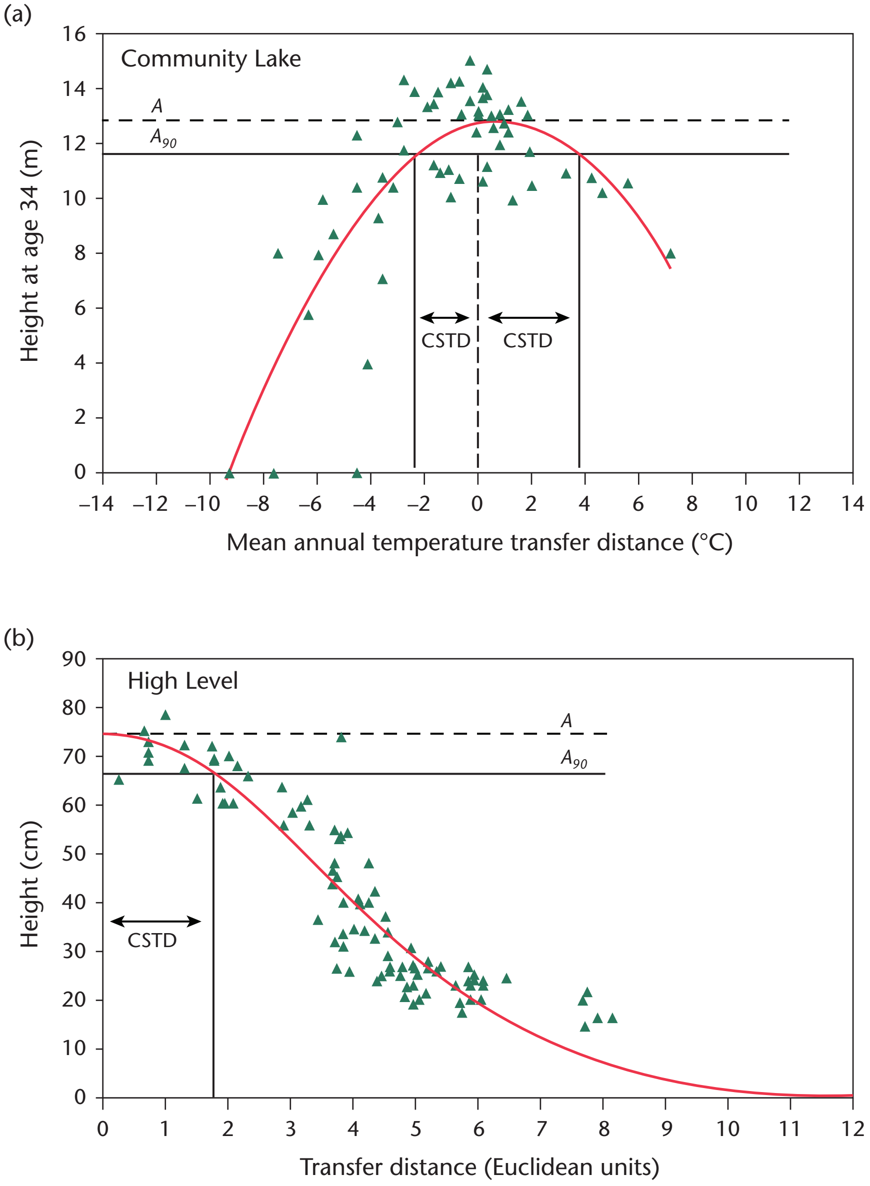

FIGURE 2 *Examples of univariate (top) and multivariate (bottom, from O'Neill et al. 2014) transfer functions relating population height to population climate transfer distance. Top graph shows height of lodgepole pine populations growing at the Community Lake Illingworth provenance test site. Bottom graph shows height of interior spruce natural stand seed sources at the High Level provenance test site. Also shown are the fitted transfer function and critical seed transfer distance (CSTD) at 90% of* A *(i.e., at* A_{90}*), where* A *is the expected height of a climatically local natural stand seed source growing at the test sites. Critical seed transfer distance is the maximum distance seed should be moved to ensure that height is at least 90% of the expected height of local seed sources.*

A third genetic class—natural stand superior provenance seed sources (i.e., Genetic Class B+)—consists of seed collected from provenances that have demonstrated superior growth over that of local populations in provenance trials. Seed from these geographically defined point sources may be deployed within specified natural stand seed planning zones and elevation transfer limits.

Decision support tools used to implement seed transfer systems have been developed for most forestry jurisdictions; however, these tools differ considerably in design and use. Table 1 summarizes some of these tools.

TABLE 1 *Zone type and delineation variables for selected seed transfer systems*

Location	Decision support tool	Zone type	Delineation variable	Website	Citation
United States and southern Canada	Seedlot selection tool	Focal point	Climate	https://seedlotselectiontool.org/sst/	
United States and Canada	SeedWhere	Focal point	Climate	https://cfs.nrcan.gc.ca/publications?id=20952	McKenney 1999
British Columbia	Seed Planning and Registry (SPAR): Orchard seed sources	Fixed	Ecosystems, physiography, and geography	www.gov.bc.ca/seedregistry	Snetsinger 2004; Ying and Yanchuk 2006
British Columbia	Seed Planning and Registry (SPAR): Natural stand seed sources	Fixed and focal point	Ecosystems and physiography (fixed); latitude, longitude, and elevation (focal point)	www.gov.bc.ca/seedregistry	Snetsinger 2004; Ying and Yanchuk 2006
Alberta	Alberta seedlot selection	Fixed	Ecosystems	https://sites.ualberta.ca/~ahamann/teaching/various/adaptation/5-seed--breeding-zones.html	Downing and Pettapiece (compilers) 2006
Sweden	PlantVal (planter's guide)	Focal point	Climate	www.kunskapdirekt.se/sv/KunskapDirekt/Alla-Verktyg/Planters-guide-2/	
Ontario	Focal point seed zones for northwest Ontario	Focal point	Adaptive variation patterns	www.nrcresearchpress.com/doi/abs/10.1139/b96-148	Parker and van Niejenhuis 1996
Washington	Seed zones of Washington	Fixed and focal point	Climate, physiography, and adaptive variation patterns (fixed) and elevation (focal point)	www.dnr.wa.gov/search/site/tree%20seed%20zones	Randall and Berrang 2002
Mexico	Seed zones of Mexico	Fixed	Ecosystems		Conkle 2004
Oregon	Seed zones of Oregon	Fixed and focal point	Climate, physiography, and adaptive variation patterns (fixed); and elevation (focal point)	www.oregon.gov/ODF/AboutODF/Pages/MapsData.aspx	
California	California Tree Seed Zones	Fixed and focal point	Climate and physiography	http://frap.cdf.ca.gov/data/frapgisdata-sw-seed_zones_download.php	Buck et al. 1970
British Columbia	Climate-based seed transfer (proposed)	Focal zone	Climate	www.gov.bc.ca/climatebasedseedtransfer	

4.1 Adaptation, Deployability, and Ease of Use

British Columbia's current geography-based seed transfer system—relatively unchanged since its introduction in 1987—presents several limitations. Analysis of the climates of seed sources and seed planning units suggests that some seed is transferred considerable climatic distances or is unnecessarily restricted in its deployment (see Appendix 1 in O'Neill et al. 2008b). The system is also complicated, requiring reference to geographic co-ordinates, elevation, seed planning zones or units, and biogeoclimatic zones for both seed sources and plantations, as well as the seed genetic class to determine seed transfer eligibility. New data or analyses can require costly updates to seed planning zone and unit data sets and maps. Also, the current system provides no information on the degree of suitability of a seed source for a given location, as each seed source is classified only as eligible or ineligible in each location. Consequently, it is not possible to tailor deployment of limited seed inventories to maximize adaptation.

4.2 Assisted Migration

As climates change, plantations established with locally adapted seed sources are predicted to become increasingly maladapted, leading to increased susceptibility to pests and reduced plantation growth (St. Clair and Howe 2007; O'Neill et al. 2008a; Sturrock et al. 2011; Rehfeldt et al. 2014a). Indeed, recent reports of significant pest infestations (Carroll et al. 2004; Woods et al. 2005; Woods 2011), forest decline (Hennon et al. 2005; Allen et al. 2010; Michaelian et al. 2011), failure of some plantations to meet productivity expectations (Woods and Bergerud 2008; Mather et al. 2010), and reduced carbon sequestration of forests (Kurz et al. 2008) are consistent with these predictions, and may be a manifestation of climate changes observed over the last century in the province (Spittlehouse 2008) and a harbinger of future challenges.

Assisted migration in a forestry context (i.e., planting tree seed sources from climates slightly warmer than that of the planting site) is widely recognized as a key strategy to lessen climate change impacts to plantations (Wang et al. 2010; Gray and Hamann 2011; Kreyling et al. 2011; Leech et al. 2011; Pedlar et al. 2012; Gray and Hamann 2013; Lu et al. 2014; Rehfeldt et al. 2014a; Koralewski et al. 2015). By nudging tree populations in the direction of climate change, assisted migration helps maintain forest resilience, health, and productivity by restoring populations to climates in which their finely tuned phenotypes, wrought through millennia of natural selection, are best adapted.

British Columbia and several other jurisdictions have made allowances for assisted migration on a limited scale (Snetsinger 2004; Pedlar et al. 2011); however, a new system of seed transfer—one based primarily on climate rather than on geography—is required to facilitate the effective, safe, and efficient implementation of assisted migration across the province.

4.3 Opportunities

Several factors have created significant opportunities to improve British Columbia's seed transfer system and, therefore, to improve the health and growth of the province's forests. These include:

- recent advances in genecological research methods (Hamann et al. 2000; O'Neill and Aitken 2004; St. Clair et al. 2005; Wang et al. 2006, 2010; Rehfeldt and Jaquish 2010; Hamann et al. 2011; Ukrainetz et al. 2011; Leites et al. 2012b);

- new data from old and new provenance trials (Xie 2008; Krakowski and Stoehr 2009, 2011; Russell and Krakowski 2012; O'Neill et al. 2014);
- the advent of GIS and fine-scale climate data (Parker and van Niejenhuis 1996; Crowe and Parker 2005; Rehfeldt and Jaquish 2010; Wang et al. 2012);
- improved General Circulation Models (Knutti et al. 2013); and
- new genomics tools capable of assessing seed source climate adaptation (Hamilton et al. 2013).

Most importantly, an improved seed transfer system will result in better matching of seed sources with the environments to which they are most closely adapted, reducing the risk of forest health and productivity losses, and facilitating deployment of high-value seedlots to the most productive sites (Wang et al. 2006).

If British Columbia's system of seed transfer were to delineate seed zones along BEC unit boundaries, it would dovetail with the existing basis of forest management in the province and eliminate the expense associated with creating and maintaining maps specific for seed transfer. Also, constraining zone size using climate rather than geography could help identify recurrent climates in disparate locations, increasing seed deployability (the area to which each seedlot can be safely used), further reducing costs by reducing the number of seedlot collections required, or the need to maintain large seed inventories.

5 DESIGNING A NEW SEED TRANSFER SYSTEM FOR BRITISH COLUMBIA

5.1 Objectives

The goal of any seed transfer system is to foster plantation health and productivity at an acceptable cost (Morgenstern 1996). To meet this goal, the CBST Science Foundation working group identified improved matching of seedlots to plantation environments as its primary objective. Additional objectives include:

- facilitating effective assisted migration to reduce climate change impacts to forests;
- allowing wider seedlot deployability and flexibility;
- increasing ease of use;
- simplifying updates to the decision support tool;
- quantifying adaptation of seed source options to improve seed source deployment; and
- integrating with other natural resource management decision support tools.

5.2 Selecting a Seed Transfer System and Delineation Variable

In assessing seed transfer approaches, two key aspects—the system and the delineation variable—were examined in detail. The choice of which system and delineation variable to use in a new seed transfer approach was addressed by the working group in a transparent and quantifiable manner using a weighted scoring approach. Objectives were identified for each aspect (see Table 2 and Section 5.1), and an importance weight (1–10) was assigned to each objective. Each seed transfer system option (fixed, focal point, and focal zone) and delineation variable option (climate, biogeocli-

TABLE 2 *Weighted scoring method for assessing seed transfer system and delineation variable options for a new seed transfer approach in British Columbia*

	Seed transfer system						
	Raw score (1–10)				Weighted score		
Objectives	**Fixed**	**Focal point**	**Focal zone**	**Weight (1–10)**	**Fixed**	**Focal point**	**Focal zone**
Improves matching of seed source with plantation climate	1	10	9	10	10	100	90
Facilitates effective assisted migration	1	10	10	7	7	70	70
Increases seed source deployability and flexibility	1	10	9	3	3	30	27
Increases ease of use	10	1	8	5	50	5	40
Simplifies updating of the decision support tool	1	1	7	5	5	5	35
Quantifies adaptation of seed source options to optimize seed source deployment	1	10	10	3	3	30	30
Integrates with other natural resource management decision support tools	4	1	10	3	12	3	30
Total					**90**	**243**	**322**

	Delineation variable												
	Raw score (1–10)							Weighted score					
Objectives	**Geography**	**Seed planning zones**	**Climate**	**BEC zones**	**BEC units**	**Adaption**	**Weight (1–10)**	**Geography**	**Seed planning zones**	**Climate**	**BEC zones**	**BEC units**	**Adaption**
Improves matching of seed source with plantation climate	1	4	7	5	8	10	10	10	40	70	50	80	100
Facilitates effective assisted migration	1	3	10	3	10	10	7	7	21	70	21	70	70
Increases seed source deployability and flexibility	1	4	7	5	8	10	3	3	12	21	15	24	30
Increases ease of use	10	5	1	10	10	1	5	50	25	5	50	50	5
Simplifies updating of the decision support tool	10	6	4	8	8	1	5	50	30	20	40	40	5
Quantifies adaptation of seed source options to optimize seed source deployment	2	3	10	3	8	10	3	6	9	30	9	24	30
Integrates with other natural resource management decision support tools	1	1	1	10	10	1	3	3	3	3	30	30	3
Total								**129**	**140**	**219**	**215**	**318**	**243**

matic ecosystem classification zone, BEC unit, geographic zone, genetic zone, and seed planning zone) was scored (1–10) in relation to the degree to which it meets each objective. Scores for each option were then multiplied by the importance weight and summed. Although the scores and weights were somewhat subjective, we expect that a different evaluation team using the same set of objectives would arrive at consistent rankings.

The focal zone seed transfer system met all objectives well, scoring somewhat better than the focal point system, and much better than the fixed zone system. The BEC units option for delineating seed zones also scored well for all objectives, exceeding climate, BEC zones, and genetic adaptation delineations by a moderate amount, and seed planning units and geographic variables by a considerable margin (Table 2).

5.3 System Overview

For a natural resource manager wishing to find eligible seed sources of a given tree species for a given plantation, the proposed system identifies a set of BEC units climatically similar to the BEC unit of the plantation. We refer to the BEC unit of the seed source as the "focal zone" and the set of climatically similar BEC units as the "genetic suitability area." This approach to guiding seed transfer has been proposed in Alberta, where candidate seed sources for a plantation are ranked according to the multivariate climate distance between the seed source ecosystem mean climate and the plantation ecosystem mean climate (Gray and Hamann 2011). Conversely, for a seedlot owner, the system identifies for a given seedlot a set of BEC units that is climatically similar to the BEC unit of the seedlot and in which the seedlot is expected to be well adapted. Here the BEC unit of the plantation is the "focal zone" and the set of climatically similar BEC units is the "genetic suitability area." The genetic suitability area is then overlaid onto the species suitability area, with their common area identifying the seedlot procurement and deployment areas (see Section 7 for the rationale and methods for the overlaying procedure).

Identification of the genetic suitability area involved three steps. First, for each species, a transfer function (see Section 5.5) relating population climate transfer distance to population mean height was created using provenance trial data. Second, climate distances between each pair of BEC units were calculated. Third, climate distances between BEC unit pairs were then substituted into the transfer function to estimate the relative height growth associated with transferring seed between each pair of units. Transfers where the relative height growth exceeds a minimum threshold are used to identify the genetic suitability area. The CBST Policy working group will decide on a threshold minimum relative height to be used.

5.4 Data

Provenance and progeny data were obtained for interior spruce, lodgepole pine, and coast and interior Douglas-fir.[6] Data were retained from those test sites containing a wide climate or latitude range and sampling intensity of populations. Additionally, data from young test sites (< 5 years) were excluded. Appendix 1 contains details regarding the data used in the analysis.

Normalized values for 21 annual climate variables for the "current" period (i.e., 1961–1990) were obtained for all populations and test sites using ClimateWNA, version 4.7 (Wang et al. 2012).[7] The BEC unit values and climate

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[6] Results for the other species are in development.

[7] For further details, see: http://climatewna.com.

data for the same 21 variables were also obtained for all points on a 1600-m grid of the province and for each seedlot registered in the B.C. Ministry of Forests, Lands and Natural Resource Operation's Seed Planning and Registry (SPAR) system.[8]

Before use in transfer function (Section 5.5) and climate migration distance analyses (Section 6.1), the set of 21 climate variables was reduced. Incorporating assisted migration into the proposed seed transfer system will be most effective when the variables used to guide seed source migration include those that have changed considerably. Therefore, change in each of the 21 climate variables during the 30-year periods centred on 1915 and 1995 was calculated using the set of gridded points for the province and standardized by dividing the change by each variable's variability (standard deviation during the period 1961–1990) to obtain an index of change for each variable. The five variables showing the smallest change index were omitted (i.e., summer heat moisture index [SHM], precipitation as snow [PAS], annual heat moisture ratio [AHM], Hargreave's reference evaporation [EREF], and Hargreave's climatic moisture deficit [CMD]). Degree-days below and above 18 (DD < 18 and DD > 18) were also omitted because they were developed for use primarily in non-biological areas (Durmayaz et al. 2000).

To further simplify the analysis and increase independence among retained climate variables, an additional seven variables were removed by omitting one of each highly correlated ($r > 0.90$) pair, leaving a final seven climate variables (i.e., mean annual temperature [MAT]; mean cold month temperature [MCMT]; summer–winter temperature differential [TD]; log of mean annual precipitation [log10MAP]; mean summer precipitation [MSP]; degree days > 5 [DDGT5]; and extreme maximum temperature [EXT]). Latitude (LAT), a surrogate for photoperiod (which is only weakly correlated with the retained climate variables) was added to the seven climate variables, for a total of eight variables used in the analyses. All eight climate variables[9] have been repeatedly identified as drivers of population differentiation in North American genecology analyses (Parker and van Niejenhuis 1996; Andalo et al. 2005; St. Clair and Howe 2007; Hamann et al. 2011; Ukrainetz et al. 2011; Russell and Krakowski 2012; Joyce and Rehfeldt 2013; Rehfeldt et al. 2014b; Yang et al. 2015).

5.5 Transfer Functions

Transfer functions were developed from provenance data to calculate growth impacts expected to be incurred for a given climate transfer distance. Climate distances between provenances and test sites were expressed in Euclidean[10] units—a consolidated index of the eight climate variables—to capture more fully the complexity of the multivariate climate space. However, first to ensure that Euclidean climate distances (EDs) between test sites and provenances (and between pairs of BEC units—see next section) are scaled similarly, test sites, provenances, BEC unit means, and the large set of 1.6-km gridded pro-

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[8] For information about SPAR, see www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/tree-seed/seed-planning-use/spar.

[9] For simplicity, we refer to the eight variables as "climate" variables, and distances calculated using these variables as "climate distances," acknowledging that latitude is included among the eight variables.

[10] Euclidean distance (ED) is the square root of the sum of the individual squared distances (d) between two points in multivariate space. $\text{ED} = \sqrt{d_1^2 + d_2^2 + \cdots + d_n^2}$

vincial points were combined into a single data set, and values of each of the eight climate variables scaled to standard normal deviates. EDs were then calculated and individual transfer functions [Equation 1] relating population mean height (Y) to ED were developed for each site by fitting a non-linear half-normal function using the NLIN procedure in SASstatistical software:[11]

$$\mathrm{Y} = A \times \exp \frac{-0.5 \times \mathrm{ED}^2}{\sigma^2} \qquad (1)$$

where A and σ^2 are model parameters that describe the scalar (maximum fitted response value) and rate of decline of the response value, respectively. Data from the least informative sites ($R^2 < 0.30$ for interior spruce and Douglas-fir; $R^2 < 0.55$ for lodgepole pine) were excluded.

Data from the remaining sites were then pooled. To facilitate pooling of data from sites of different productivity, population mean heights, Y, were divided by A, the intercept of the individual transfer functions (i.e., by the modelled height of a local population) for each site to calculate the relative population height values (HTp) at each site. Next, using HTp as the dependent variable, a single, pooled transfer function [Equation 2] was fitted for each species, lending stability to the function by extending the climate transfer range beyond that of the individual transfer functions (Carter 1996).

To ensure that HTp = 1 at the zero transfer distance, A was set at 1.0. Also, to allow differences in transferability in different climates to be represented in the pooled transfer function, σ^2 was replaced with an exponentiated linear combination of one of the site variables: $\exp(b_0 + b_1 \times \mathrm{SV})$, where b_0 and b_1 are constants and SV = the site variable (i.e., latitude or one of the seven climate variables). (This approach is similar to that of Leites et al. (2012a) who predict height as a function of a single site climate variable and a univariate transfer distance.)

$$\mathrm{HTp} = 1.0 \times \exp\left(\frac{-0.5 \times \mathrm{ED}^2}{e^{b_0 + b_1 \times \mathrm{SV}}}\right) \qquad (2)$$

The pooled model containing the site variable that yielded the strongest R^2 was selected as the final model: lodgepole pine $R^2 = 0.66$, SV = MAT; interior spruce $R^2 = 0.77$, SV = TD; Douglas-fir $R^2 = 0.35$, SV = LAT) (Figure 3).

The half-normal function necessarily peaks at zero transfer distance, making it impossible to identify climates of populations that are taller than local populations (i.e., non-local optimality). Inability to identify superior non-local populations and quantify their superiority is a disadvantage of this function; however, this is outweighed by the advantages of the half-normal function: it accommodates Euclidean values, which are exclusively positive (O'Neill et al. 2014); it is relatively insensitive to situations where a "tail" is lacking on one side of a transfer function, a frequent situation in provenance tests and a common source of spurious results in genecology analyses (Wang et al. 2010; Leites et al. 2012a); it has a logical form (broad, flat vertex and asymptotic tail); and the Euclidean climate distance used in the function provides additional stability across a range of climates, particularly when it is composed of multiple climate variables that are weakly correlated to each other, as is the case in these analyses. Perhaps, most importantly, it obviates

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[11] Data analyses were generated using SAS/STAT software, Version 9.3 of the SAS System for Windows Copyright © 2002–2010 SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, N.C., USA.

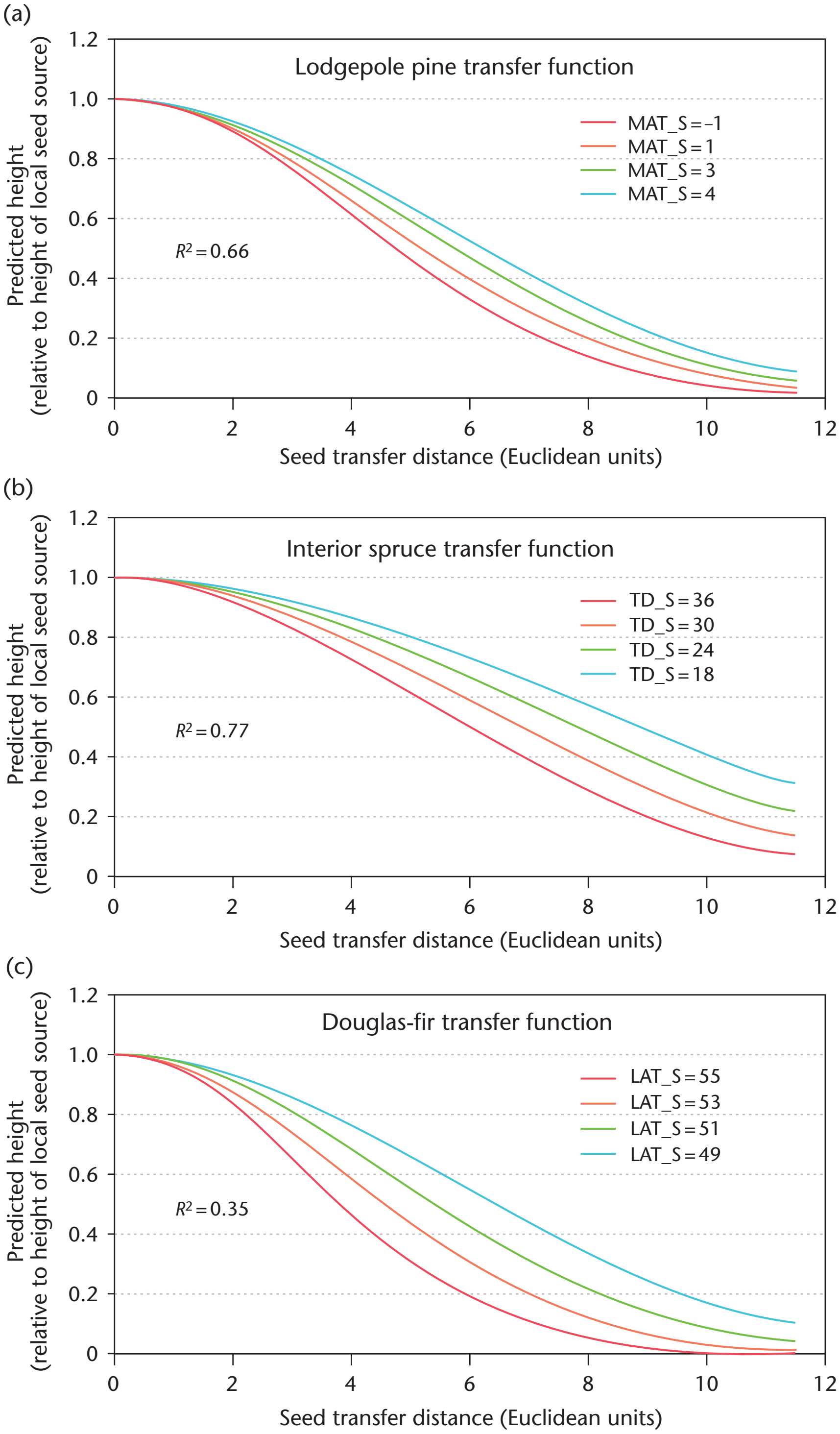


FIGURE 3 *Results of pooled transfer function analysis. Euclidean climate transfer distance is a multivariate index of several climate variables and latitude, with zero climate transfer distance indicating a local seed source. Note: "_S" indicates a site value; MAT = mean annual temperature (°C); TD = temperature difference, the difference between the warmest and coldest months (°C); LAT = latitude.*

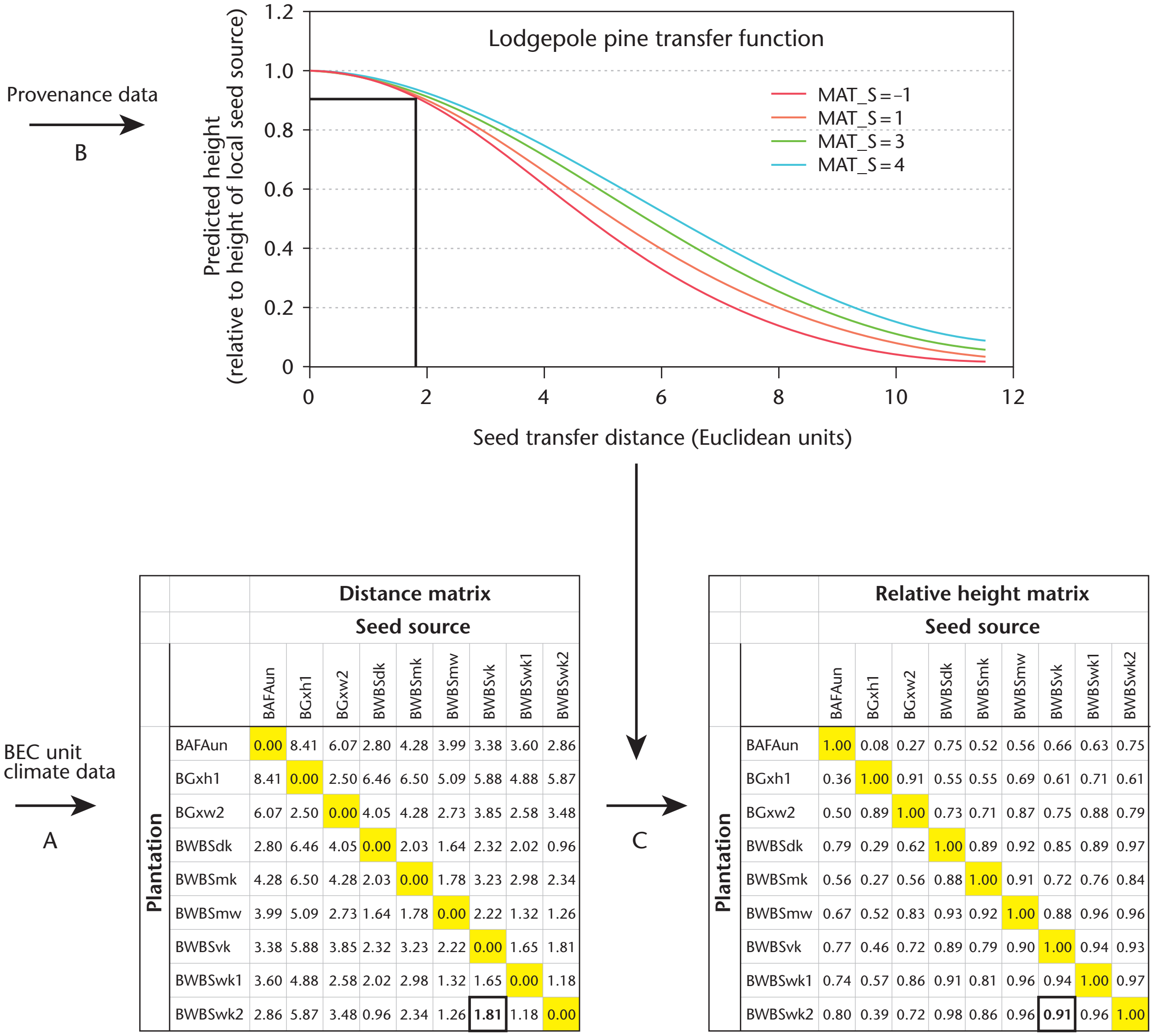
reliance on the function to estimate recent evolutionary lag, which is estimated poorly by transfer functions (see Section 6.1 below).

5.6 Transfer Impacts

To estimate impacts of transferring seedlots between each pair of BEC units, the means of each of the climate variables for each BEC unit were calculated using the large set of grid-point values (Section 5.4; see Appendix 2). Mean climate values of each BEC unit were then used to calculate the Euclidean climate distance between each pair of BEC units. To calculate the expected height of a seedlot from each BEC unit when transferred to (i.e., grown in) each BEC unit, relative to the expected height of a local seedlot grown in each BEC unit, the Euclidean climate distances were substituted into the final pooled transfer function for each species, along with the value of the site climate variable identified in the final step of Section 5.5. Relative height values are presented in a 205 × 205 BEC unit matrix, in which columns represent seed source BEC units and rows represent plantation BEC units. Figure 4 and Appendix 4 illustrate the procedures followed to develop the relative height matrix.

Height is a strong measure of fitness in trees (Wu and Ying 2004) and is the most frequently used trait in tree genecology analyses. Compound variables or more direct measures of fitness may be stronger (St. Clair et al. 2005; Savolainen et al. 2007; Russell and Krakowski 2012) but are often not feasible to measure in tree field provenance trials because of tree size. We tested height, survival, individual tree volume, and area-based volume as candidate response variables in our transfer functions; however, all resulted in functions having considerably greater error than did height, and were therefore rejected in favour of height. Additionally, while height may not be the strongest component of fitness, it fits the early evolutionary biologists' definitions of a focal trait that best reflects fitness of the whole organism (Dobzhansky 1956; Mayr 1983; and see discussion in Ying and Yanchuk 2006) and provides a more tangible interpretation than compound indices of fitness.

Inter–BEC unit seed transfer impacts could also be estimated directly from population response functions. Although use of population response functions would have allowed for identification of transfers that resulted in supra-local growth (Wang et al. 2006), incomplete sampling of seed source and test site BEC units in provenance tests would have resulted in growth estimates for only a fraction of potential inter–BEC unit transfers. Alternatively, universal transfer functions (O'Neill et al. 2008a) or universal response functions (Wang et al. 2010) could have been used; however, the number of provenance test sites is usually inadequate to develop reliable universal transfer functions, and the range and distribution of population and test site climates is inadequate to develop reliable universal response functions. Considering these issues, the provenance data available, and a desire for a consistent method of estimating inter–BEC unit transfer impacts that provides stable values across a wide range of climates for all species, we chose to use half-normal site-specific transfer functions based on Euclidean climate distances.



Distance matrix

Plantation \ Seed source	BAFAun	BGxh1	BGxw2	BWBSdk	BWBSmk	BWBSmw	BWBSvk	BWBSwk1	BWBSwk2
BAFAun	0.00	8.41	6.07	2.80	4.28	3.99	3.38	3.60	2.86
BGxh1	8.41	0.00	2.50	6.46	6.50	5.09	5.88	4.88	5.87
BGxw2	6.07	2.50	0.00	4.05	4.28	2.73	3.85	2.58	3.48
BWBSdk	2.80	6.46	4.05	0.00	2.03	1.64	2.32	2.02	0.96
BWBSmk	4.28	6.50	4.28	2.03	0.00	1.78	3.23	2.98	2.34
BWBSmw	3.99	5.09	2.73	1.64	1.78	0.00	2.22	1.32	1.26
BWBSvk	3.38	5.88	3.85	2.32	3.23	2.22	0.00	1.65	1.81
BWBSwk1	3.60	4.88	2.58	2.02	2.98	1.32	1.65	0.00	1.18
BWBSwk2	2.86	5.87	3.48	0.96	2.34	1.26	**1.81**	1.18	0.00

Relative height matrix

Plantation \ Seed source	BAFAun	BGxh1	BGxw2	BWBSdk	BWBSmk	BWBSmw	BWBSvk	BWBSwk1	BWBSwk2
BAFAun	1.00	0.08	0.27	0.75	0.52	0.56	0.66	0.63	0.75
BGxh1	0.36	1.00	0.91	0.55	0.55	0.69	0.61	0.71	0.61
BGxw2	0.50	0.89	1.00	0.73	0.71	0.87	0.75	0.88	0.79
BWBSdk	0.79	0.29	0.62	1.00	0.89	0.92	0.85	0.89	0.97
BWBSmk	0.56	0.27	0.56	0.88	1.00	0.91	0.72	0.76	0.84
BWBSmw	0.67	0.52	0.83	0.93	0.92	1.00	0.88	0.96	0.96
BWBSvk	0.77	0.46	0.72	0.89	0.79	0.90	1.00	0.94	0.93
BWBSwk1	0.74	0.57	0.86	0.91	0.81	0.96	0.94	1.00	0.97
BWBSwk2	0.80	0.39	0.72	0.98	0.86	0.96	**0.91**	0.96	1.00

FIGURE 4 *Illustration of the procedures followed to quantify the expected impacts of seed transfer between BEC units. (A) Provenance data is used to develop a pooled transfer function relating Euclidean climate transfer distance to relative height (i.e., height relative to height of local seed source). (B) BEC unit climate data is used to calculate the Euclidean climate distance between all pairs of BEC units. (C) Euclidean climate distances between pairs of BEC units are substituted into the transfer function to estimate relative height of transferring seed sources between each pair of BEC units. For example, BEC units BWBSwk2 and BWBSvk are moderately different climatically, separated by 1.81 Euclidean units. To predict the relative height of lodgepole pine seed from the BWBSvk planted in the BWBSwk2, where the mean annual temperature is 0.46 °C, one can interpolate between the site MAT –1 (red) and +1 (orange) lines at a Euclidean climate distance of 1.81 to obtain a relative height of 0.91. Transfers between climatically similar BEC units (small Euclidean climate transfer distances) result in expected relative heights approaching that of a local seed source (i.e., 1.0), whereas transfers between climatically disparate BEC units (large Euclidean climate transfer distances) result in short relative height values (e.g., <0.90). See Appendix 4 for calculations involved in HTp calculation.*

6.1 Climate Migration Distance

Climates are seldom stationary on an evolutionary time scale, creating a situation in which plant populations are continually “chasing” the climate for which they are most fit (i.e., their climatic optimum) (see the “Red Queen Hypothesis” in Savolainen et al. 2007; Aitken et al. 2008; Benton 2009). The adaptation lag—the distance between the present climate where a population resides and its climatic optimum (Savolainen et al. 2007; Kuparinen et al. 2010; Gray and Hamann 2013)—closes during periods of climate stability and widens as climates depart from long-term norms (Wilczek et al. 2014). As the rate of climate change in the last century has vastly outpaced the capacity of tree populations to respond through migration and natural selection, it may be assumed that populations best adapted to the present climate of a plantation are more likely to be found in locations where the plantation’s present climate existed a century ago, rather than locally.

Even if populations selected for reforestation are optimally adapted to the present climate of a plantation, they will likely be substantially maladapted at harvest (i.e., at rotation: ca. 50 years after planting on the Coast, and ca. 70 years after planting in the Interior) when the mean temperature may be 2–4°C warmer than at present. Furthermore, populations optimally adapted to the climate at rotation may not perform well during the sensitive establishment phase. Weighing the risk of maladaptation during seedling establishment versus the risk of maladaptation at stand rotation, we propose planting populations optimally adapted to the climate expected to reside at the plantation at a quarter of the rotation age (ca. 12 and 17 years after planting on the Coast and in the Interior, respectively) (O’Neill et al. 2008b; Ukrainetz et al. 2011).

To identify the expected optimum climate from which to procure seed for a plantation (i.e., the target procurement climate), it is therefore necessary to consider past climate change (i.e., adaptation lag from the beginning of the industrial era to present) *and* future climate change (from present to a quarter of the rotation age), which when summed form the “climate migration distance” (O’Neill et al. 2008b; Ukrainetz et al. 2011). Adding the climate migration distance (or “climate migration vector” when multiple climate variables are employed) to the current climate of the plantation locates the current climate from which to procure seed expected to be optimally adapted to the plantation over the rotation (i.e., the target procurement climate). Table 3 shows an example for BEC unit ESSFdm; Appendix 3 contains a full list of migration distances.

Since proxy climate estimates made before establishment of the first weather stations in British Columbia lack the accuracy required for migrating seed sources, and weather recording stations were sparse until the mid-1940s, we calculate past climate change using records beginning in 1945 when stations were more widespread and accurate. The climate migration distance was calculated for each BEC unit and for each climate variable as the sum of the amount the climate has changed from 1945 to 2017, and the amount the climate is expected to change from 2017 to 2029 (coastal BEC units) or from 2017 to 2034 (interior BEC units). Thirty-year climate normals centred on 1945 were used to represent past (1945) climate. Present (2017) and future (2029

TABLE 3 *Climate variable estimates of ESSFdm BEC unit. To account for recent past and future climate change, the amount the climate has changed in the recent past and the amount the climate is expected to change in the next quarter rotation are estimated for the BEC unit and added to obtain the "climate migration distance." The climate migration distance is added to the plantation's current climate to obtain the current climate of the procurement target.*

	Climate variable[a]						
	MAT	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**
Plantation climate (ESSFdm)	1.5	−9.4	22.6	1088	339	847	31.3
Climate migration distance	1.4	1.6	−0.1	157	73	232	1.7
Target procurement climate	2.9	−7.8	22.5	1245	412	1079	33.0

a MAT = mean annual temperature; MCMT = mean cold month temperature; TD = summer–winter temperature differential; log10MAP = log of mean annual precipitation; MSP = mean summer precipitation; DDGT5 = degree days > 5; and EXT = extreme maximum temperature.

and 2034) climates were interpolated or extrapolated from a linear trend between 30-year climate normals centred on 1945 and the average of 10 general circulation model projections (see Table 6 in Murdock and Spittlehouse 2011) centred on 2025. For a detailed description of the procedure, see Ukrainetz et al. (2011).

6.2 Calculating Relative Heights Using Assisted Migration

To integrate assisted migration into the proposed focal zone seed transfer system (i.e., to facilitate selection of seedlots from BEC units that are slightly warmer than the plantation), the procedures for calculating relative heights (Section 5.6) were repeated, after first adding a "climate migration distance" to the current climate of each plantation BEC unit, creating a "repositioned" plantation BEC unit climate. Euclidean climate transfer distances were then calculated between each (unchanged) seedlot BEC unit climate and all repositioned plantation BEC unit climates. The new Euclidean climate transfer distances were used together with the repositioned plantation BEC unit climates to re-calculate the relative height matrix, effectively shifting the seed procurement target for a given plantation (i.e., focal zone) and its associated genetic suitability area to slightly warmer climates, and seed deployment target for a given seed source and its associated genetic suitability area to slightly colder plantations. See illustrations of the effect of repositioning the genetic suitability area in climate space (Figure 5) and geographic space (Figure 6). Appendix 5 illustrates the calculation of relative height (HTp) when assisted migration is used. Transfers where the relative height growth exceeds a minimum threshold are used to identify the migrated genetic suitability areas.

In summary, migrating (repositioning) the target procurement climate using a climate migration distance was selected as the approach to achieve assisted migration because:

- a climate migration distance is quantified and transparent;
- it considers both past and future climate change;
- it is BEC–unit specific;
- it yields what we believe are logical results; and
- it can be easily adjusted over time.

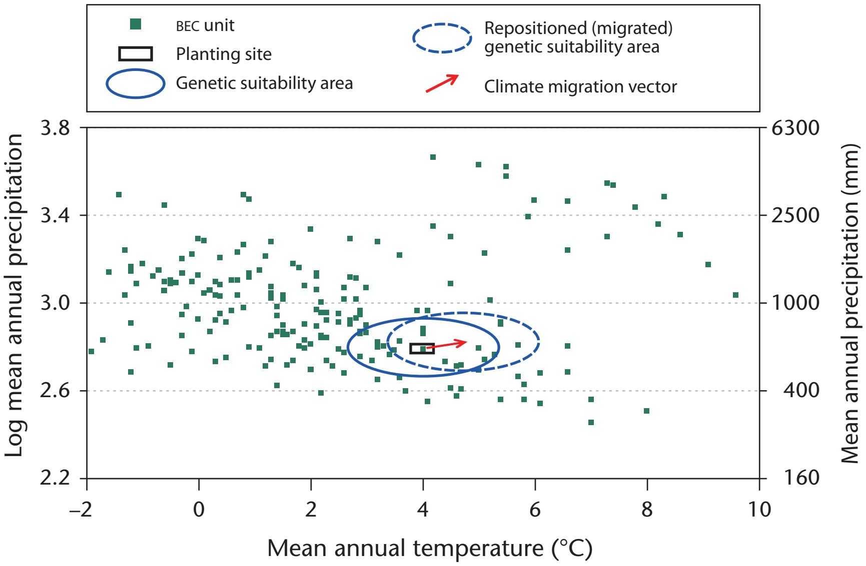
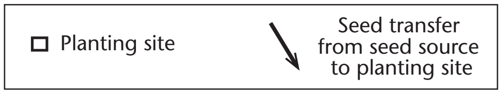


FIGURE 5 *Scatterplot of BEC unit means across two climate axes. In the proposed focal zone seed transfer system, the genetic suitability area is centred on the planting site BEC unit (i.e., the focal zone). Seed from anywhere inside the genetic suitability area can be planted at the planting site; however, when assisted migration is used, the focal zone is repositioned using the climate migration vector so that the repositioned genetic suitability area is centred on the head of the climate migration vector.*

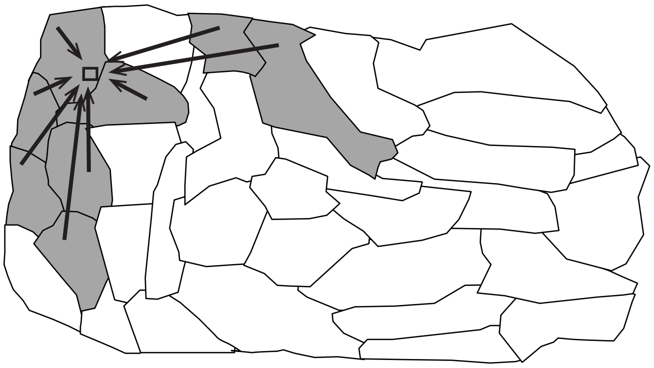
Furthermore, climate variables used in the climate migration distance vector are the same as those used in the transfer functions, and are therefore related to population height growth.

7 SPECIES SUITABILITY

To provide additional assurance that seed is deployed to climates only where it is well adapted, we overlaid a second set of BEC units where the *species* grows well (i.e., the species distribution, or the "species suitability area") onto the set of BEC units comprising the genetic suitability area for each BEC seed source unit, generally following the approach of Rehfeldt and Jaquish (2010). BEC units common to both sets were retained as the "seedlot deployment area" (Figure 7). In other words, any BEC units deemed to be suitable for planting seed from a given BEC unit were excluded if they fell outside of the species' modelled distribution. For each seed source BEC unit, current (1975) genetic suitability areas overlaid onto the current (1975) species distribution were used to identify seedlot deployment areas without assisted migration, whereas migrated genetic suitability areas (see Section 6.2) overlaid onto the migrated species distribution for 2029 (coast BEC zones) and 2034 (interior BEC zones) (see below) were used to identify migrated seedlot deployment areas.



(a) Focal zone seed transfer system – without assisted migration



(b) Focal zone seed transfer system – with assisted migration

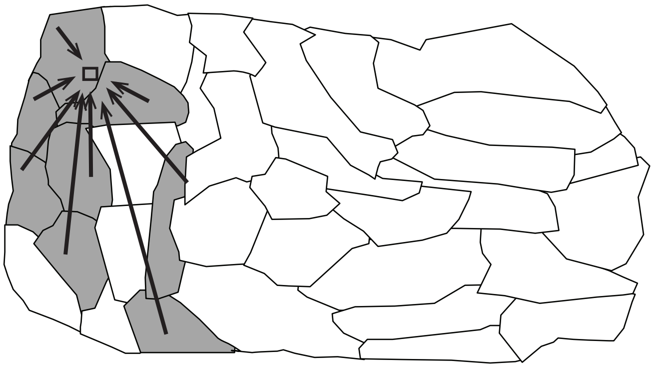


FIGURE 6 *Example of focal zone seed transfer system (a) without and (b) with assisted migration. In (a), the genetic suitability area consists of all zones that are climatically similar to the focal zone (i.e., the zone containing the planting site); in (b), the genetic suitability area shifts toward warmer zones south of the focal zone.*

Species suitability was modelled as probability of presence for each species in each BEC unit by Tongli Wang. Training models were developed in Random Forests (Breiman 2001) to predict the probability of species' presence for each tree species, using presence/absence data from 42 225 B.C. Ministry of Forests, Lands and Natural Resource Operations botanical plots and 10 671 U.S. Department of Agriculture Forest Service inventory plots from nine neighbouring states and their corresponding 1961–1990 climate values (21 annual variables and 56 seasonal variables). Final models, arrived at through an optimization procedure, used 15–20 annual and seasonal climate variables to predict probability of presence of each species at each point on an 800-m grid of British Columbia, using climate values of the grid points for three 30-year climate normal periods: 1961–1990, 2011–2040, and 2041–2070 (hereafter referred to by their midpoints, 1975, 2025, and 2055).

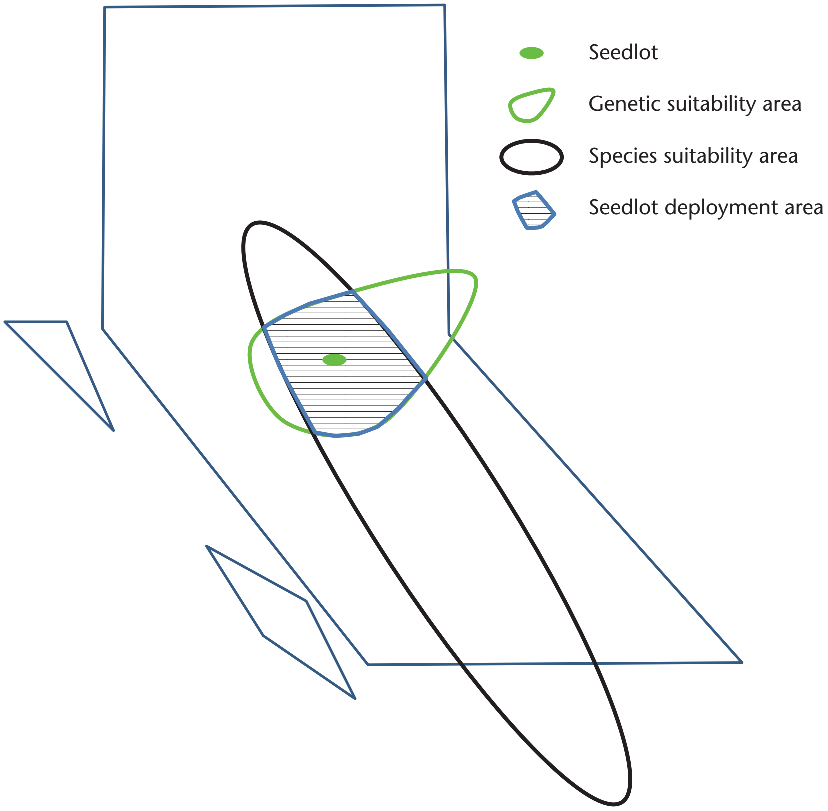


FIGURE 7 *Illustration showing the overlay of genetic and species suitability areas to identify seedlot deployment area for a seedlot within British Columbia.*

Fifteen general circulation models at each of two relative concentration pathways (4.5 and 8.5) were used to model probability of presence in 2025 and 2055. Average probability of presence values were then calculated at each grid point for 2025 and 2055. Finally, probability of presence was averaged over each BEC unit for each of the three periods, then interpolated to 2029 (coast BEC zones) and 2034 (interior BEC zones). A species was deemed present in a BEC unit when its probability of presence value exceeded 0.40. This threshold for species presence was selected because species' relative basal area increases sharply at this value (data not shown). Furthermore, species were generally absent from the *Reference Guide for Forest Development Plan Stocking Standards*[12] in BEC units having probability of presence less than 0.40, whereas species were seldom absent (i.e., listed as "preferred" or "acceptable" species) in BEC units having probability of presence values greater than 0.40.

Species selection using BEC units and site soil moisture and nutrient regime considerations will continue as the first step in reforestation decisions, capitalizing on significant effort linking species suitability with ecosystems. A tool in development by FLNRO will identify the future BEC unit climate of

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[12] B.C. Ministry of Forests, Lands and Natural Resource Operations. 2014. Reference guide for forest development plan stocking standards (Microsoft Excel spreadsheet). Resource Practices Branch, Victoria, B.C. Available at: www.for.gov.bc.ca/hfp/silviculture/Stocking_stds/ Reference Guide incorporating climate change Feb 17_14.xlsm.

specified cutblock locations, enabling users to select species appropriate for future climates of their cutblocks, and facilitating assisted migration of species (i.e., assisted range expansion). Seedlot selection, as described above, will continue to follow the species selection step. The species suitability component of the seedlot selection procedure will complement the BEC unit migration procedure by providing additional assurance of appropriate species selection during assisted migration.

8 ORCHARD SEED

8.1 Deployment

Families in progeny trials are seldom transferred sufficiently widely to obtain reliable estimates of how far orchard seedlots can be safely transferred. Consequently, transferability (i.e., critical seed transfer distance) of orchard seedlots may best be estimated from transfer functions developed from provenance trials (i.e., from natural stand populations) where transfer distances are typically much wider than they are in progeny trials; however, parents from orchard seedlots originate from multiple BEC units and, therefore, from a wider climate range compared with parents from natural stand seedlots, which usually originate from a single BEC unit. As a result, orchard seedlots may be more deployable than suggested by transfer functions constructed with natural stand populations. Adoption of a lower minimum relative height for selection of orchard seedlots than natural stand seedlots in the Chief Forester's Standards (Snetsinger 2004) would afford a convenient mechanism to provide greater deployability to orchard seedlots. For example, use of a minimum relative height of 0.970 and 0.975 for orchard and natural stand seedlots, respectively, would provide orchard seedlots with approximately 15% greater deployability than natural stand seedlots.

Climates in which natural stand seedlots perform optimally are often similar to the climates (or pre-industrial climates) of the natural stand parents' origin (Wu and Ying 2004).[13] Likewise, the climates in which orchard seedlots perform optimally is usually similar to the climates (or pre-industrial climates) of the *orchard parents' origin* (O'Neill et al. 2014). Nevertheless, several generations of selection could shift the climatic optimum of the orchard population, particularly if the testing climate differs substantially from that of the parents' origin, potentially creating a new "landrace." Fortunately, the mean climates of test sites and parents are usually very similar in British Columbia (see Appendix 1 in O'Neill et al. 2008b). In addition, most breeding programs are entering only their second generation of selection, and so the optimum deployment climate for orchard seedlots should be relatively similar to that of the parents' origin. Therefore, to facilitate inclusion of orchard seedlots in the proposed focal zone seed transfer system, we have assigned each orchard seedlot to the BEC unit having the climate most similar to the mean climate origin of the orchard parents; breeders may modify this assignment, taking into consideration a range of additional data that could inform seed transfer decisions, such as genetic-by-environment interactions and progeny test data.

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[13] Exceptions may be related to various factors, including adaptation lag or gene swamping of peripheral populations, or an artefact related to lack of adequate regression "tails" (Aitken et al. 2008; Ukrainetz et al. 2011).

8.2 Genetic Worth

Orchard seedlots are likely to be optimally adapted when planted in climates close to the pre-industrial climate of the orchard parents, but genetic worth[14] values are most accurate at the mean climate of the *test sites*; deployment of orchard seedlots substantially outside the test site climates would warrant adjustment of genetic worth values; however, long-distance transfer is infrequent currently, and will be even less so when transfer is based on climate. Assisted migration and conservative, climate-based critical seed transfer distances will help ensure that orchard seed sources continue to be planted in climates similar to those in which testing occurred, obviating the need to adjust genetic worth values.

Although estimates differ widely, particularly in the short term, most researchers suggest that, in the long term, climate change will reduce forest productivity. Assisted migration is expected to offset these losses, and may even increase productivity in some areas (Wang et al. 2010). While it is difficult to estimate the magnitude of climate change impacts (losses) and offsets that may accrue through assisted migration, particularly at rotation age, comparable impacts of seed transfer on growth for orchard and natural stand seed (O'Neill et al. 2014) suggest that both seed source types will be affected similarly by climate change and assisted migration. Consequently, the relative growth superiority of orchard seedlots over natural stand seedlots is not expected to be substantially altered by climate change or assisted migration. We therefore suggest that the assignment of genetic worth values remains unchanged in the proposed seed transfer system.

9 NATURAL STAND SUPERIOR PROVENANCE SEEDLOTS

Natural stand superior provenance seedlots (i.e., genetic class B+) are natural stand seedlots that are assigned a small genetic worth (usually 2–3% for growth) and wider deployability than other natural stand seedlots, on the basis of their superior growth in provenance trials. As with orchard seedlots, the relative superiority of B+ seedlots over natural stand seedlots is not expected to be altered because of climate change or assisted migration. Consequently, the CBST Science Foundation working group proposes to maintain existing genetic worth values for B+ seedlots. Furthermore, as the proposed deployability of natural stand seedlots exceeds current deployability of B+ seedlots, the working group also proposes applying the same deployability to B+ seedlots as it does to other natural stand seedlots, which will help simplify the proposed system.

10 SUMMARY

Figure 8 summarizes the main features of the proposed climate-based seed transfer system, and how these features will achieve the goals and objectives defined by the CBST Technical working group.

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[14] Genetic worth is the average level of expected genetic gain for a selected trait associated with a particular orchard seedlot and is calculated as the mean breeding value of the parents, weighted by their gametic contribution to the seedlot.

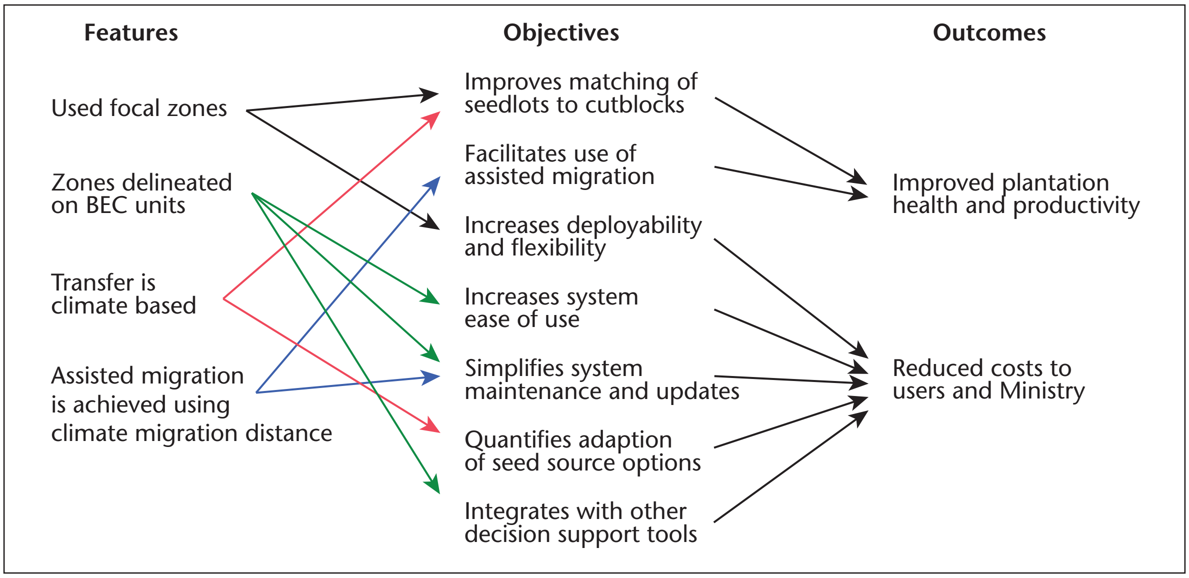

FIGURE 8 *Illustration showing how the main features of the proposed climate-based seed transfer system address each objective and how the objectives fulfill the goals identified by the working group.*

The following summary highlights the key contributions of the proposed climate-based seed transfer system.

- One of the most important aspects of the proposed system is the improved matching of seed sources to climates. This is achieved by using climate rather than geography to constrain seed transfer and by applying the climate-based transfer functions developed with the most recent provenance test data.
- The proposed simple and transparent system of assisted migration is intended to ensure that plantations receive seedlots that are optimally adapted to the plantation climate over the rotation. This is achieved by using seed from BEC units that are slightly warmer than the plantation BEC unit. The climate "distance" between the plantation and target seed source BEC units is determined by adding recent past climate change and the amount the climate is expected to change in the next quarter rotation.
- The ability to deploy orchard and natural stand seedlots is increased in the proposed system through the use of focal zones, which provide greater seedlot choice and flexibility for seed users.
- The proposed system uses species and BEC unit origin of the seed source as the sole determinants of seed deployability; seed planning zones and units, BEC zones, geographic co-ordinates, and elevations are not required to ascertain seed transfer eligibility. Ease of use is further simplified by applying the same seed transfer system to all three genetic classes (A, B, and B+).
- New phenotypic test results, new genomic information, or new climate data can be readily incorporated into the proposed system via changes to the height matrix. Similarly, information from alternative predictive models (response functions, universal transfer functions, and universal response functions) or genomics analyses can be readily incorporated when available.

- Genetic suitability values estimated in the proposed system facilitate strategic seed deployment of scarce or high-gain seed to areas where it is expected to be best adapted.
- Delineating zones on BEC units would dovetail with the existing basis of forest management in British Columbia, and obviate the need to create and maintain additional data sets and redundant sets of maps.

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APPENDIX 1 Provenance data used to develop transfer functions for the Climate-based Seed Transfer project

Species	EP #	Project description	No. test sites analyzed	Data
Interior spruce	670.71.12	Sx climate change/genecology provenance trial	17	Height at age 6
Douglas-fir	1200	Submaritime provenance trial (Interior and Coast)	8	Height at age 15
	710.01	Trinity Valley provenance trial	1	Height at age 15
	976.07.01	Nass–Skeena provenance trial	3	Height at age 15
Lodgepole pine	657.06	Illingworth provenance trial	43	Height at age 32

APPENDIX 2 Mean values of latitude and seven climate variables for 205 BEC units used in Euclidean climate distance calculations

To remove scale effects, values of each variable were first converted to standardized normal deviates by subtracting the variable's provincial mean from the BEC unit mean and dividing the difference by the provincial standard deviation. See provincial means and standard deviations at bottom of table.

		Climate variable[a]							
BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP[b]**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
BAFAun	57.461	−2.833	−13.441	22.169	1299	510.70	344.26	25.537	3.113
BAFAunp	52.474	−0.593	−10.246	19.159	1257	291.92	426.02	28.347	3.099
BGxh1	49.149	7.956	−4.022	23.433	323	131.92	2041.63	38.597	2.510
BGxh2	50.702	7.004	−5.706	24.428	287	136.83	1884.48	37.573	2.458
BGxh3	51.335	5.797	−6.862	24.087	365	176.43	1640.95	36.589	2.562
BGxw1	50.332	5.370	−6.339	22.875	363	157.93	1496.54	35.979	2.560
BGxw2	51.634	4.595	−8.283	24.389	377	201.74	1430.62	35.832	2.576
BWBSdk	58.319	−0.515	−14.179	26.532	521	247.99	737.22	29.860	2.717
BWBSmk	58.880	−1.229	−18.824	33.611	482	300.55	1015.66	32.478	2.683
BWBSmw	56.231	1.158	−13.758	28.486	515	309.28	1108.73	32.382	2.712
BWBSvk	59.525	2.720	−10.109	24.379	1318	428.53	1083.72	30.492	3.120
BWBSwk1	55.140	2.181	−10.051	24.333	710	375.64	1070.42	31.399	2.851
BWBSwk2	56.896	0.458	−12.225	25.615	566	373.84	884.39	30.088	2.753
BWBSwk3	59.196	−1.054	−14.202	27.015	622	408.81	764.87	29.431	2.794
CDFmm	49.029	9.561	3.022	13.838	1085	198.44	1996.52	34.609	3.035
CMAun	56.192	−1.404	−11.535	20.310	3130	874.08	384.85	26.479	3.496
CMAunp	51.025	0.765	−7.395	17.375	3143	691.52	554.33	29.095	3.497
CWHdm	49.668	8.631	1.287	15.403	2062	452.14	1830.44	34.347	3.314
CWHds1	50.128	6.565	−3.055	19.313	1752	360.96	1566.60	34.618	3.244
CWHds2	52.263	4.479	−5.307	19.348	1237	270.94	1185.71	33.203	3.092
CWHmm1	49.461	7.809	1.001	15.075	2726	432.61	1629.52	34.415	3.435
CWHmm2	49.293	6.641	−0.125	15.352	2941	435.75	1391.22	33.571	3.468
CWHms1	50.040	4.456	−4.935	19.258	2019	424.35	1169.55	33.125	3.305
CWHms2	52.197	5.937	−2.033	16.352	2490	587.09	1291.62	32.369	3.396
CWHun	51.076	1.260	−8.680	19.680	1116	220.00	666.20	30.620	3.048
CWHvh1	50.312	8.289	3.275	11.002	3060	648.28	1575.31	31.348	3.486
CWHvh2	53.083	7.318	1.872	11.946	3529	921.96	1381.68	30.729	3.548
CWHvm1	50.899	7.395	0.796	14.141	3461	739.36	1501.08	32.585	3.539
CWHvm2	51.298	5.528	−1.696	15.494	3802	844.72	1176.77	31.741	3.580
CWHwh1	53.546	7.344	2.004	11.924	2008	487.64	1369.09	31.000	3.303
CWHwh2	53.296	6.038	0.601	12.402	2946	661.79	1115.51	30.595	3.469
CWHwm	56.617	4.162	−5.970	19.545	2243	647.25	1086.09	30.275	3.351
CWHws1	54.617	5.065	−4.850	19.379	1683	416.52	1262.84	32.317	3.226

Appendix 2 *Continued*

		Climate variable[a]							
BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP[b]**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
CWHws2	53.868	3.198	−6.466	19.092	1902	467.00	922.84	30.936	3.279
CWHxm1	49.366	9.108	2.131	14.723	1502	285.35	1914.16	34.724	3.177
CWHxm2	49.588	8.204	1.365	14.851	2311	378.71	1706.83	34.307	3.364
ESSFdc1	49.615	1.931	−8.271	21.174	799	332.68	852.51	31.905	2.902
ESSFdc2	49.686	2.173	−7.498	20.269	1008	277.29	844.02	31.637	3.003
ESSFdc3	51.167	1.694	−9.149	21.541	741	329.74	812.91	31.671	2.870
ESSFdcp	50.761	−0.200	−10.109	20.359	964	374.91	521.45	29.368	2.984
ESSFdcw	49.941	0.843	−9.036	20.688	952	364.45	677.18	30.479	2.979
ESSFdk1	49.402	1.326	−9.895	22.964	1055	367.14	837.14	30.893	3.023
ESSFdk2	50.712	0.180	−11.519	23.453	1139	454.15	706.74	30.455	3.056
ESSFdkp	50.615	−1.567	−12.064	21.873	1385	527.97	451.55	27.760	3.142
ESSFdku	51.084	−1.219	−12.664	22.910	1400	621.25	509.49	28.667	3.146
ESSFdkw	50.203	−0.517	−11.395	22.478	1227	477.28	584.77	29.053	3.089
ESSFdm	49.281	1.508	−9.431	22.611	1088	338.91	847.23	31.294	3.036
ESSFdmp	49.501	−0.569	−10.763	22.088	1141	368.16	571.50	28.838	3.057
ESSFdmw	49.476	0.149	−10.371	22.463	1118	356.22	668.72	29.700	3.049
ESSFdv1	50.525	1.302	−7.896	18.941	1063	262.84	650.92	30.295	3.026
ESSFdv2	50.934	0.643	−8.629	18.921	922	232.66	567.43	29.792	2.965
ESSFdvp	50.687	−0.473	−8.872	17.763	1273	300.17	406.63	28.298	3.105
ESSFdvw	50.695	0.215	−8.613	18.338	1154	274.94	495.71	29.116	3.062
ESSFmc	55.863	0.360	−10.860	22.374	892	327.57	669.17	29.024	2.950
ESSFmcp	56.854	−1.099	−11.965	22.120	1228	431.38	485.01	27.195	3.089
ESSFmk	53.736	1.203	−8.947	19.829	1632	390.72	640.42	29.174	3.213
ESSFmkp	53.834	0.134	−9.838	19.713	1936	435.70	507.18	28.249	3.287
ESSFmm1	53.077	0.429	−10.783	22.475	1219	488.51	701.11	29.158	3.086
ESSFmm2	53.027	0.308	−12.371	24.102	1261	532.34	715.38	28.868	3.101
ESSFmmp	53.042	−0.764	−11.338	21.608	1331	525.72	521.67	27.456	3.124
ESSFmmw	52.615	0.329	−10.814	22.600	1087	416.71	688.86	29.186	3.036
ESSFmv1	53.699	0.869	−10.957	22.467	633	290.07	705.88	29.913	2.801
ESSFmv2	55.030	1.374	−9.910	22.965	876	426.58	883.38	29.999	2.942
ESSFmv3	55.771	0.152	−11.293	23.061	746	330.52	684.56	29.428	2.872
ESSFmv4	56.869	−0.872	−12.506	23.960	639	356.72	617.91	27.948	2.805
ESSFmvp	56.119	−1.208	−11.878	22.254	810	384.10	503.75	27.315	2.909
ESSFmw	50.804	1.828	−7.729	19.537	1444	317.89	761.14	30.938	3.159
ESSFmw1	49.607	2.671	−7.029	20.349	1965	472.32	931.90	32.320	3.293
ESSFmw2	50.396	1.737	−7.495	19.289	1509	348.10	734.94	30.452	3.179
ESSFmwp	50.674	−0.142	−8.910	18.495	1682	373.43	471.57	28.595	3.226
ESSFmww	50.087	1.278	−7.838	19.452	1900	443.91	690.93	30.295	3.279

Appendix 2 *Continued*

		Climate variable[a]							
BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP[b]**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
ESSFun	57.024	−0.095	−12.124	23.604	1258	405.24	645.45	28.374	3.100
ESSFunp	57.000	−1.197	−13.042	23.457	1461	468.01	505.31	27.360	3.165
ESSFvc	51.521	0.366	−10.763	22.333	1623	489.06	675.74	30.267	3.210
ESSFvcp	51.526	−1.292	−11.594	21.281	1743	521.26	447.79	28.085	3.241
ESSFvcw	51.419	−0.252	−10.840	21.530	1609	555.67	564.85	29.206	3.207
ESSFwc1	50.093	1.901	−9.181	22.497	1202	420.05	902.40	32.370	3.080
ESSFwc2	51.853	0.643	−10.425	22.144	1274	461.51	701.22	30.430	3.105
ESSFwc3	54.410	0.375	−10.690	22.357	1212	474.06	684.83	29.391	3.083
ESSFwc4	50.209	0.930	−9.833	22.071	1309	466.24	749.56	31.135	3.117
ESSFwc5	49.414	2.105	−8.944	22.521	1336	411.15	921.25	31.902	3.126
ESSFwc6	49.409	1.140	−9.476	21.950	1417	431.33	763.05	30.633	3.151
ESSFwcp	52.604	−0.683	−11.066	21.431	1418	516.34	526.69	28.379	3.152
ESSFwcw	51.556	−0.270	−10.848	21.623	1370	488.87	572.43	29.394	3.137
ESSFwk1	53.003	1.426	−9.633	21.708	970	424.15	775.20	30.876	2.987
ESSFwk2	55.023	1.268	−10.491	23.597	1186	447.67	879.66	30.453	3.074
ESSFwm	49.909	0.871	−10.178	22.903	1378	435.95	786.01	30.941	3.139
ESSFwmp	50.077	−0.982	−11.241	22.126	1517	487.22	542.84	29.011	3.181
ESSFwmw	49.804	0.036	−10.592	22.554	1339	434.32	668.98	30.032	3.127
ESSFwv	55.921	0.720	−10.232	22.128	1086	395.83	720.97	29.498	3.036
ESSFwvp	56.089	−0.432	−11.017	21.874	1241	437.81	570.48	28.223	3.094
ESSFxc1	49.273	1.393	−7.923	19.882	742	264.05	705.94	30.673	2.870
ESSFxc2	50.308	1.640	−8.632	21.109	718	315.87	804.11	31.482	2.856
ESSFxc3	50.994	1.066	−8.542	19.912	623	236.10	676.92	29.845	2.794
ESSFxcp	50.207	0.013	−8.870	19.045	849	281.82	511.48	28.707	2.929
ESSFxcw	50.098	0.310	−8.749	19.217	838	269.22	547.68	29.315	2.923
ESSFxv1	51.944	−0.316	−10.460	19.773	885	253.90	459.75	28.918	2.947
ESSFxv2	51.245	−0.294	−9.941	19.412	713	271.18	466.58	29.167	2.853
ESSFxvp	51.604	−1.272	−10.540	18.592	1093	285.14	338.17	27.663	3.039
ESSFxvw	51.105	−0.109	−9.015	18.667	605	260.94	477.73	28.749	2.781
ICHdk	51.941	3.182	−8.969	23.282	668	277.99	1110.70	33.686	2.825
ICHdm	49.291	2.908	−8.861	23.696	890	284.94	1103.29	33.416	2.949
ICHdw1	49.397	5.381	−6.346	23.301	803	269.89	1516.59	36.104	2.905
ICHdw2	49.363	4.968	−6.292	22.532	622	246.54	1411.33	35.961	2.794
ICHdw3	51.658	4.038	−8.070	23.400	730	305.77	1267.83	34.215	2.863
ICHmc1	55.828	2.834	−8.381	22.026	860	336.25	1022.33	31.573	2.934
ICHmc2	55.295	3.981	−7.276	21.842	769	305.59	1197.54	32.633	2.886
ICHmk1	49.710	3.637	−7.369	22.134	676	280.50	1160.60	34.431	2.830
ICHmk2	51.176	3.250	−8.222	22.553	640	280.72	1102.01	33.581	2.806

Appendix 2 *Continued*

		Climate variable[a]							
BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP[b]**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
ICHmk3	52.305	2.938	−8.938	22.813	725	322.40	1053.33	33.118	2.860
ICHmk4	50.204	2.694	−9.765	24.448	841	325.15	1104.07	33.524	2.925
ICHmm	52.892	2.055	−10.187	23.911	933	368.01	993.14	31.777	2.970
ICHmw1	51.660	2.255	−10.490	24.748	905	295.05	1049.76	33.196	2.957
ICHmw2	50.077	4.088	−7.481	23.050	929	340.46	1280.72	34.740	2.968
ICHmw3	51.452	3.872	−8.050	23.225	928	361.95	1242.33	34.052	2.968
ICHmw4	49.281	2.997	−8.119	22.545	1176	367.09	1062.05	32.943	3.070
ICHvc	56.334	2.227	−9.114	22.272	902	322.96	929.26	30.560	2.955
ICHvk1	51.682	2.149	−9.824	23.458	1372	448.04	973.70	32.450	3.137
ICHvk2	53.901	2.752	−9.510	23.557	1045	428.71	1076.25	32.301	3.019
ICHwc	57.064	2.102	−10.690	24.044	1156	354.17	952.89	30.164	3.063
ICHwk1	51.407	2.606	−9.346	23.443	1176	412.46	1045.23	33.042	3.071
ICHwk2	52.550	2.746	−9.225	23.059	801	351.25	1033.30	33.067	2.904
ICHwk3	53.570	2.890	−9.389	23.484	930	406.44	1088.46	32.382	2.968
ICHwk4	53.253	2.467	−9.245	22.606	893	395.88	975.02	32.186	2.951
ICHxw	49.130	6.611	−5.282	23.469	635	214.33	1755.12	37.605	2.803
IDFdc	50.742	3.214	−7.739	21.402	629	169.23	1039.40	32.991	2.799
IDFdk1	50.304	3.557	−7.237	21.628	460	191.43	1120.34	33.541	2.662
IDFdk2	49.951	3.960	−6.701	21.438	615	213.09	1185.39	34.140	2.789
IDFdk3	51.660	3.160	−8.864	23.092	451	230.38	1107.94	33.991	2.654
IDFdk4	51.885	2.183	−9.737	22.904	391	204.74	945.02	33.567	2.592
IDFdk5	51.004	3.520	−9.929	25.686	607	250.21	1292.84	35.040	2.784
IDFdm1	49.372	4.729	−6.391	22.308	523	216.84	1355.72	35.359	2.719
IDFdm2	49.770	4.576	−8.326	25.083	517	229.25	1446.61	35.972	2.713
IDFdw	51.607	1.956	−8.615	20.507	648	179.48	795.92	31.949	2.812
IDFmw1	50.391	5.341	−6.402	23.068	582	247.96	1501.93	36.057	2.765
IDFmw2	51.217	5.101	−7.044	23.537	552	239.77	1473.92	35.551	2.742
IDFun	49.443	5.678	−6.044	23.261	641	246.43	1572.91	36.278	2.807
IDFww	50.745	5.226	−5.391	21.103	1035	221.99	1411.63	34.915	3.015
IDFww1	50.420	5.395	−5.465	21.560	816	201.78	1452.03	35.109	2.912
IDFxc	50.696	4.955	−6.377	22.135	496	154.10	1389.72	34.862	2.696
IDFxh1	49.787	5.665	−5.750	22.587	462	188.10	1543.85	36.174	2.664
IDFxh2	50.540	4.718	−6.847	22.722	405	173.95	1371.94	35.105	2.608
IDFxh4	49.086	6.083	−5.654	23.150	478	195.17	1643.91	37.546	2.679
IDFxk	50.432	4.540	−8.994	25.893	413	196.68	1487.49	36.261	2.616
IDFxm	51.890	3.669	−8.745	23.750	398	217.68	1238.76	34.928	2.600
IDFxw	51.089	4.071	−7.990	23.277	357	176.11	1271.44	34.605	2.553
IMAun	51.746	−2.299	−11.887	20.379	1552	521.28	342.65	26.343	3.191

Appendix 2 *Continued*

		Climate variable[a]							
BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP[b]**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
IMAunp	50.308	0.720	−8.378	19.210	1714	399.49	619.56	29.646	3.234
MHmm1	51.483	4.087	−3.457	16.244	3804	848.56	955.31	31.002	3.580
MHmm2	53.415	1.984	−7.651	19.368	2183	530.47	756.32	30.005	3.339
MHmmp	54.861	0.892	−8.953	19.517	2980	771.39	594.18	28.477	3.474
MHun	59.624	0.725	−11.754	24.129	1277	395.67	768.67	28.629	3.106
MHunp	58.781	−0.011	−10.496	21.330	1962	598.14	579.11	27.415	3.293
MHwh1	53.493	4.955	−1.703	14.322	4312	1125.06	1004.89	30.147	3.635
MHwh2	53.144	5.487	0.110	12.345	4199	951.09	1003.33	30.148	3.623
MHwhp	53.715	4.150	−2.697	14.713	4630	1161.65	879.89	29.788	3.666
MSdc1	50.616	2.329	−7.750	20.175	836	204.18	846.18	31.632	2.922
MSdc2	51.581	0.539	−9.446	19.492	824	228.54	551.53	29.924	2.916
MSdc3	50.993	1.341	−8.736	20.069	713	198.60	696.21	30.866	2.853
MSdk1	49.419	3.001	−9.059	24.010	792	290.65	1128.57	33.443	2.899
MSdk2	50.562	2.063	−10.585	24.715	789	338.48	1021.25	33.194	2.897
MSdm1	49.562	3.261	−7.355	21.640	637	265.44	1074.91	33.499	2.804
MSdm2	49.825	2.948	−7.200	20.808	746	243.72	988.55	32.717	2.873
MSdm3	50.999	2.922	−8.213	22.057	573	265.02	1027.12	33.151	2.758
MSdv	51.208	0.409	−10.441	20.739	1079	250.08	567.73	30.223	3.033
MSmw1	49.730	3.620	−6.541	20.751	1661	406.57	1101.39	33.516	3.220
MSmw2	50.473	2.843	−7.164	20.107	1293	291.49	927.25	32.003	3.112
MSun	52.262	1.505	−8.468	19.875	792	185.33	720.85	31.105	2.899
MSxk1	49.615	2.505	−7.350	20.472	615	227.88	900.32	32.097	2.789
MSxk2	50.679	2.645	−7.981	21.340	479	220.90	955.10	32.271	2.680
MSxk3	50.910	2.015	−7.937	20.369	497	219.76	826.04	30.916	2.696
MSxv	52.335	0.292	−11.281	21.973	543	251.64	599.61	30.337	2.735
PPdh2	49.506	5.799	−7.157	25.213	426	199.65	1669.33	37.265	2.630
PPxh1	49.574	7.042	−4.696	23.073	366	155.61	1831.88	37.465	2.564
PPxh2	50.572	6.095	−6.043	23.537	348	142.63	1665.98	36.569	2.541
PPxh3	49.027	6.606	−5.391	23.504	486	198.56	1757.09	38.204	2.687
SBPSdc	52.881	1.964	−10.460	23.436	502	264.29	916.77	32.561	2.701
SBPSmc	53.048	1.555	−10.602	22.875	523	217.80	818.28	31.804	2.719
SBPSmk	52.358	2.266	−9.603	22.754	549	278.58	942.84	32.695	2.739
SBPSxc	52.084	1.409	−10.508	22.646	420	197.18	796.58	32.361	2.623
SBSdh1	53.015	3.035	−9.899	24.674	734	307.12	1169.98	33.006	2.866
SBSdh2	52.923	1.495	−11.808	25.140	1048	448.42	938.88	31.058	3.020
SBSdk	54.023	2.434	−10.231	23.739	515	221.68	1001.76	32.297	2.712
SBSdw1	52.421	3.429	−8.935	23.455	581	278.40	1164.37	33.888	2.764
SBSdw2	52.798	3.051	−9.322	23.515	548	268.63	1107.73	33.425	2.739

Appendix 2 *Concluded.*

		Climate variable[a]							
BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP[b]**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
SBSdw3	54.155	2.649	−10.105	24.154	598	262.79	1069.79	32.381	2.777
SBSmc1	52.077	2.212	−9.180	22.137	695	316.82	907.88	32.120	2.842
SBSmc2	54.762	1.814	−10.288	23.137	636	257.14	884.10	31.120	2.803
SBSmc3	53.335	1.300	−10.981	22.988	555	261.94	778.71	31.289	2.744
SBSmh	53.063	4.431	−9.024	24.984	543	263.54	1406.81	34.752	2.735
SBSmk1	54.716	1.920	−10.880	24.548	682	282.14	980.96	31.751	2.834
SBSmk2	56.017	1.704	−11.933	26.204	548	247.38	1050.67	31.979	2.738
SBSmm	51.631	2.287	−9.116	22.150	696	318.22	917.65	32.472	2.843
SBSmw	53.154	3.169	−9.160	23.355	659	317.68	1116.49	33.146	2.819
SBSun	57.560	1.482	−10.969	24.090	720	238.69	894.66	29.888	2.857
SBSvk	54.248	2.578	−9.897	24.082	1044	402.62	1081.25	32.234	3.019
SBSwk1	54.013	2.470	−10.206	24.080	822	340.28	1040.37	32.347	2.915
SBSwk2	55.643	1.490	−11.252	25.136	746	335.84	985.51	31.316	2.873
SBSwk3	55.360	1.888	−10.642	24.066	626	273.97	947.34	32.087	2.797
SWBmk	58.219	−1.685	−13.557	24.552	684	374.38	558.30	27.787	2.835
SWBmks	57.850	−2.355	−13.291	23.120	805	409.96	425.90	26.315	2.906
SWBun	59.123	−1.922	−14.933	25.783	602	266.89	535.64	28.263	2.779
SWBuns	59.333	−2.634	−15.018	24.889	732	315.78	428.75	27.109	2.865
SWBvk	59.634	0.823	−11.999	24.871	1847	644.20	829.21	29.154	3.267
SWBvks	59.530	−0.600	−13.128	24.514	2806	986.41	621.21	27.839	3.448
Mean	**54.480**	**1.221**	**−10.348**	**23.011**		**409.33**	**875.47**	**30.646**	**2.971**
Standard Deviation	**3.338**	**3.042**	**5.309**	**5.292**		**230.79**	**371.20**	**2.850**	**0.297**

a LAT = latitude; MAT = mean annual temperature; MCMT = mean cold month temperature; TD = summer–winter temperature differential; MAP = mean annual precipitation; MSP = mean summer precipitation; DDGT5 = degree days > 5; EXT = extreme maximum temperature; and log10MAP = log of mean annual precipitation.

b MAP is not used in the calculation of Euclidean distances between BEC units; however, it is presented in this Appendix to assist users in gaining a better sense of the climate distances between BEC units.

APPENDIX 3 Migration distance values for seven climate variables of 205 BEC units

Migration distances are the distances to which the seed procurement targets are migrated to achieve assisted migration. These distances are calculated as the sum of the amount the climate has changed in the recent past (1945–2017) and the amount of change expected in the next quarter rotation (2017–2029, coast; and 2017–2034, interior). Latitude (LAT) is also used in the calculation of Euclidean distances between BEC units when assisted migration is used; however, its migration distance is zero.

	Climate variable[a]						
BEC unit	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**
BAFAun	1.221	1.055	0.480	3.2	21.62	123.47	1.135
BAFAunp	1.235	1.214	0.474	20.6	−3.47	146.32	0.955
BGxh1	1.393	1.560	0.096	20.4	10.17	318.30	2.557
BGxh2	1.261	0.940	0.474	20.8	6.14	286.86	2.703
BGxh3	1.210	0.982	0.590	9.5	−5.73	258.22	1.984
BGxw1	1.325	1.029	0.450	29.2	10.38	278.03	2.916
BGxw2	1.201	0.951	0.616	4.4	−9.85	241.95	1.844
BWBSdk	1.196	0.899	0.657	1.0	10.60	175.10	1.151
BWBSmk	1.377	1.733	−0.389	40.9	37.79	178.22	0.655
BWBSmw	1.243	1.500	−0.201	33.8	36.69	188.01	0.674
BWBSvk	0.908	−0.061	1.462	2.0	2.93	159.54	0.933
BWBSwk1	1.237	1.192	0.230	29.2	27.46	218.08	1.399
BWBSwk2	1.368	1.656	−0.214	52.5	48.43	190.21	0.857
BWBSwk3	1.375	1.743	−0.374	62.2	53.57	172.46	0.856
CDFmm	1.075	0.969	0.631	95.2	7.74	307.22	1.349
CMAun	1.230	0.737	0.912	2.0	−25.08	138.07	1.129
CMAunp	1.162	1.111	0.559	231.1	7.59	168.60	1.403
CWHdm	1.139	1.033	0.712	205.3	22.57	299.36	1.674
CWHds1	1.213	1.252	0.432	150.0	13.87	271.28	1.978
CWHds2	1.204	1.169	0.467	28.0	−2.74	219.07	0.892
CWHmm1	1.094	0.898	0.814	264.3	17.63	278.70	1.404
CWHmm2	1.107	0.906	0.870	307.8	24.18	264.75	1.438
CWHms1	1.226	1.272	0.473	176.3	19.51	246.82	1.989
CWHms2	1.154	1.091	0.483	52.6	−2.59	232.37	0.985
CWHun	1.249	1.192	0.413	109.3	−4.53	201.21	1.868
CWHvh1	1.005	0.926	0.359	357.6	54.47	266.17	0.853
CWHvh2	1.154	0.917	0.453	213.8	41.89	269.68	1.312
CWHvm1	1.106	0.953	0.594	286.4	29.94	265.09	1.267
CWHvm2	1.144	0.989	0.626	278.6	24.96	238.46	1.361
CWHwh1	1.050	0.594	0.474	186.9	44.75	241.83	1.002
CWHwh2	1.040	0.627	0.404	304.5	71.65	209.79	1.018
CWHwm	1.214	0.595	0.917	2.0	−10.59	225.30	0.810
CWHws1	1.429	1.060	0.944	80.6	11.13	283.39	1.353

Appendix 3 *Continued*

	Climate variable[a]						
BEC unit	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**
CWHws2	1.323	1.059	0.782	69.8	7.96	231.24	1.291
CWHxm1	1.107	0.942	0.736	150.1	14.39	305.41	1.500
CWHxm2	1.084	0.884	0.781	243.3	15.81	281.82	1.349
ESSFdc1	1.409	1.439	0.268	61.3	28.56	250.59	2.174
ESSFdc2	1.379	1.362	0.605	70.3	18.63	249.05	2.710
ESSFdc3	1.294	0.786	0.785	45.9	11.30	243.00	2.561
ESSFdcp	1.281	0.944	0.822	48.7	8.06	201.66	2.373
ESSFdcw	1.356	1.305	0.459	73.9	28.46	228.96	2.159
ESSFdk1	1.422	1.263	0.391	83.1	35.86	262.76	2.463
ESSFdk2	1.499	1.283	0.411	107.7	53.10	249.27	2.317
ESSFdkp	1.477	1.275	0.427	130.5	62.47	206.86	2.152
ESSFdku	1.610	1.291	0.499	78.9	58.62	235.31	2.372
ESSFdkw	1.515	1.305	0.432	126.9	55.25	239.98	2.319
ESSFdm	1.357	1.600	–0.137	157.1	72.53	232.30	1.693
ESSFdmp	1.413	1.548	–0.014	183.3	85.66	213.33	1.737
ESSFdmw	1.405	1.564	–0.029	179.1	82.47	224.97	1.759
ESSFdv1	1.230	1.185	0.438	67.7	3.27	210.20	1.961
ESSFdv2	1.238	1.137	0.613	59.7	–3.20	195.88	1.885
ESSFdvp	1.238	1.180	0.526	87.0	0.96	165.94	1.851
ESSFdvw	1.236	1.176	0.518	76.8	1.01	185.75	1.888
ESSFmc	1.253	1.013	0.671	0.6	7.25	185.08	1.152
ESSFmcp	1.212	0.867	0.768	2.0	–5.82	156.86	1.113
ESSFmk	1.330	1.128	0.780	44.6	9.43	202.10	1.623
ESSFmkp	1.341	1.121	0.803	62.8	11.73	182.02	1.615
ESSFmm1	1.235	0.905	0.442	38.3	8.03	210.57	2.000
ESSFmm2	1.271	1.065	0.282	44.2	3.71	213.96	2.044
ESSFmmp	1.240	0.923	0.445	42.7	7.83	187.93	1.912
ESSFmmw	1.248	1.059	0.221	42.2	2.65	211.25	2.128
ESSFmv1	1.433	1.141	0.671	20.8	–3.13	227.50	1.515
ESSFmv2	1.258	1.294	0.138	32.3	29.31	210.29	1.376
ESSFmv3	1.367	1.339	0.377	54.6	28.13	201.19	1.210
ESSFmv4	1.366	1.592	–0.032	56.5	42.02	179.43	0.988
ESSFmvp	1.338	1.414	0.200	56.2	34.84	170.35	1.138
ESSFmw	1.258	1.295	0.483	90.7	8.49	211.24	1.719
ESSFmw1	1.315	1.415	0.518	189.2	43.52	245.62	2.442
ESSFmw2	1.236	1.218	0.395	100.6	6.20	216.14	1.939
ESSFmwp	1.235	1.235	0.423	127.2	5.87	173.08	1.809
ESSFmww	1.254	1.292	0.440	154.5	24.14	213.97	2.079

Appendix 3 *Continued*

	Climate variable[a]						
BEC unit	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**
ESSFun	1.216	0.771	0.825	2.0	11.04	174.29	0.919
ESSFunp	1.217	0.787	0.810	2.0	13.24	156.83	0.952
ESSFvc	1.280	1.079	0.419	128.6	42.57	215.22	2.151
ESSFvcp	1.278	1.078	0.480	137.6	45.53	181.84	2.016
ESSFvcw	1.264	0.996	0.512	130.1	43.29	204.75	1.990
ESSFwc1	1.374	1.385	0.194	160.9	72.23	246.92	2.128
ESSFwc2	1.255	0.926	0.554	72.1	15.72	218.92	2.250
ESSFwc3	1.317	1.145	0.420	31.9	21.48	209.71	1.603
ESSFwc4	1.372	1.331	0.282	175.4	79.39	235.20	2.105
ESSFwc5	1.350	1.546	−0.161	188.1	84.14	236.12	1.760
ESSFwc6	1.343	1.545	−0.151	199.1	88.90	222.20	1.694
ESSFwcp	1.305	1.107	0.443	87.4	36.54	194.91	1.883
ESSFwcw	1.297	1.034	0.523	98.3	34.76	207.35	2.114
ESSFwk1	1.291	0.748	0.869	2.0	−9.97	238.96	2.132
ESSFwk2	1.326	1.259	0.293	40.1	32.82	215.84	1.382
ESSFwm	1.419	1.345	0.252	160.4	75.51	243.45	2.252
ESSFwmp	1.454	1.328	0.309	185.8	89.58	216.88	2.119
ESSFwmw	1.452	1.352	0.270	169.8	80.99	236.56	2.182
ESSFwv	1.261	1.019	0.669	55.5	24.41	191.57	1.080
ESSFwvp	1.251	1.039	0.628	59.8	28.16	173.51	1.093
ESSFxc1	1.354	1.509	0.598	40.3	15.02	227.06	2.618
ESSFxc2	1.390	1.115	0.639	64.9	26.53	250.96	2.577
ESSFxc3	1.224	1.060	0.713	29.3	−2.24	206.17	1.925
ESSFxcp	1.266	1.274	0.691	43.3	5.50	187.97	2.131
ESSFxcw	1.287	1.333	0.638	46.9	6.85	196.89	2.209
ESSFxv1	1.265	1.231	0.356	44.6	−9.66	162.87	1.459
ESSFxv2	1.226	1.086	0.580	32.7	−8.31	175.58	1.864
ESSFxvp	1.248	1.200	0.424	69.3	−10.49	136.92	1.586
ESSFxvw	1.211	1.061	0.781	23.1	−6.56	179.69	1.775
ICHdk	1.248	0.687	0.780	14.7	−5.27	254.15	2.370
ICHdm	1.399	1.606	−0.070	123.7	59.33	256.50	1.915
ICHdw1	1.358	1.590	−0.164	103.8	46.98	270.16	2.108
ICHdw2	1.321	1.548	−0.146	57.0	29.27	256.10	2.071
ICHdw3	1.232	0.740	0.726	34.6	2.95	259.34	2.619
ICHmc1	1.267	0.965	0.696	42.8	18.98	213.74	0.944
ICHmc2	1.303	0.936	0.826	42.6	14.14	238.56	0.991
ICHmk1	1.391	1.392	0.192	67.5	32.28	267.27	2.440
ICHmk2	1.285	0.763	0.745	37.4	8.44	260.11	2.742

Appendix 3 *Continued*

	Climate variable[a]						
BEC unit	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**
ICHmk3	1.251	0.674	0.852	2.0	−10.93	249.21	2.051
ICHmk4	1.486	1.343	0.363	81.5	41.06	283.46	2.571
ICHmm	1.240	0.917	0.406	32.7	4.75	230.66	2.184
ICHmw1	1.294	1.157	0.269	70.5	32.11	237.06	2.402
ICHmw2	1.383	1.345	0.218	127.0	57.41	274.35	2.343
ICHmw3	1.263	0.856	0.623	63.3	18.06	261.35	2.519
ICHmw4	1.318	1.552	−0.191	153.9	70.22	241.03	1.772
ICHvc	1.270	0.940	0.634	24.1	14.62	199.45	0.709
ICHvk1	1.277	1.055	0.371	101.5	32.10	239.05	2.305
ICHvk2	1.300	0.849	0.678	2.0	2.05	251.27	2.078
ICHwc	1.206	0.681	0.936	2.0	10.81	203.42	0.843
ICHwk1	1.291	1.043	0.425	99.0	35.84	247.94	2.363
ICHwk2	1.271	0.707	0.822	2.0	−9.82	253.09	2.279
ICHwk3	1.260	0.818	0.620	4.6	1.13	248.70	2.142
ICHwk4	1.308	0.783	0.811	2.0	−8.30	254.61	2.231
ICHxw	1.278	1.583	−0.281	85.0	41.33	267.95	1.955
IDFdc	1.232	1.152	0.496	37.4	−0.50	236.12	2.048
IDFdk1	1.307	1.114	0.490	33.9	10.90	254.66	2.562
IDFdk2	1.371	1.260	0.454	46.9	14.22	271.25	2.842
IDFdk3	1.212	0.833	0.670	7.6	−6.87	232.89	1.943
IDFdk4	1.246	1.090	0.455	4.4	−12.57	216.71	1.839
IDFdk5	1.457	1.221	0.339	49.6	32.27	282.68	2.477
IDFdm1	1.386	1.482	0.154	27.0	13.82	274.08	2.263
IDFdm2	1.596	1.498	0.413	58.8	32.93	325.97	2.800
IDFdw	1.253	1.220	0.285	39.9	−8.55	205.90	1.698
IDFmw1	1.452	1.107	0.573	70.3	31.63	311.78	3.155
IDFmw2	1.283	0.767	0.713	31.7	6.95	277.69	2.860
IDFun	1.363	1.594	−0.165	74.2	33.22	278.49	2.245
IDFww	1.238	1.267	0.373	68.8	5.91	251.49	1.818
IDFww1	1.223	1.198	0.417	54.8	4.51	259.66	2.169
IDFxc	1.232	1.121	0.503	29.0	0.83	255.40	2.122
IDFxh1	1.450	1.339	0.391	40.9	17.28	307.88	3.091
IDFxh2	1.290	1.009	0.500	29.8	9.13	265.96	2.684
IDFxh4	1.287	1.561	−0.114	34.4	18.95	261.15	2.107
IDFxk	1.658	1.423	0.495	44.0	25.37	333.97	2.756
IDFxm	1.205	0.927	0.620	1.0	−11.99	231.82	1.786
IDFxw	1.222	0.940	0.589	15.2	0.67	246.12	2.240
IMAun	1.312	1.103	0.498	102.3	34.41	156.06	1.913

Appendix 3 *Continued*

	Climate variable[a]						
BEC unit	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**
IMAunp	1.252	1.285	0.479	125.0	13.56	197.20	1.930
MHmm1	1.156	0.979	0.655	279.6	22.12	219.32	1.349
MHmm2	1.255	1.036	0.695	72.4	6.48	206.64	1.319
MHmmp	1.325	0.946	0.818	78.5	14.78	192.03	1.281
MHun	0.918	−0.253	1.616	2.0	−29.78	151.17	1.009
MHunp	1.058	0.391	1.075	2.0	−78.23	156.48	0.953
MHwh1	1.227	0.999	0.529	222.6	33.20	236.22	1.386
MHwh2	1.034	0.589	0.428	437.4	103.32	200.12	1.007
MHwhp	1.203	0.875	0.564	297.3	51.51	215.94	1.276
MSdc1	1.235	1.184	0.451	53.8	1.03	225.67	2.005
MSdc2	1.250	1.223	0.304	51.2	−11.21	180.37	1.667
MSdc3	1.233	1.130	0.562	39.4	−4.07	212.96	1.954
MSdk1	1.467	1.376	0.353	75.0	34.86	287.35	2.566
MSdk2	1.554	1.326	0.427	77.7	40.17	287.07	2.544
MSdm1	1.423	1.417	0.284	33.1	15.30	269.80	2.329
MSdm2	1.404	1.313	0.510	53.9	16.49	263.92	2.844
MSdm3	1.280	0.781	0.704	35.1	8.99	252.68	2.703
MSdv	1.260	1.166	0.439	85.4	−6.75	192.53	1.996
MSmw1	1.303	1.361	0.403	165.9	38.37	254.95	2.477
MSmw2	1.239	1.210	0.392	88.7	5.09	232.04	1.985
MSun	1.232	1.177	0.442	20.4	−3.95	192.36	0.943
MSxk1	1.403	1.387	0.539	38.2	14.11	252.34	2.817
MSxk2	1.266	0.939	0.586	35.2	10.74	238.68	2.377
MSxk3	1.222	1.044	0.664	22.6	0.87	221.46	2.000
MSxv	1.306	1.164	0.427	10.7	−11.72	196.09	1.619
PPdh2	1.594	1.572	0.395	52.6	30.07	341.66	2.809
PPxh1	1.479	1.461	0.236	23.7	9.60	327.94	2.963
PPxh2	1.261	1.023	0.461	25.5	6.56	274.57	2.604
PPxh3	1.250	1.557	−0.157	34.8	19.18	260.51	2.112
SBPSdc	1.302	0.956	0.661	5.7	−10.19	226.65	1.704
SBPSmc	1.339	1.271	0.371	2.5	−6.19	209.97	1.233
SBPSmk	1.255	0.833	0.688	8.8	−7.10	227.89	1.862
SBPSxc	1.274	1.162	0.373	6.5	−11.65	209.43	1.681
SBSdh1	1.210	0.859	0.427	25.5	4.70	238.57	2.219
SBSdh2	1.283	1.094	0.251	34.5	0.88	229.83	2.260
SBSdk	1.386	1.162	0.649	15.5	1.95	232.96	1.396
SBSdw1	1.230	0.705	0.801	2.2	−8.43	242.86	1.872
SBSdw2	1.269	0.815	0.764	7.4	−5.89	237.18	1.739

Appendix 3 *Concluded.*

	Climate variable[a]						
BEC unit	MAT	MCMT	TD	MAP	MSP	DDGT5	EXT
SBSdw3	1.456	1.039	0.791	27.1	6.13	260.60	1.698
SBSmc1	1.228	0.693	0.809	9.8	–8.20	231.58	1.932
SBSmc2	1.312	1.052	0.704	15.3	4.93	215.26	1.298
SBSmc3	1.414	1.137	0.604	13.5	–7.60	234.29	1.523
SBSmh	1.233	0.782	0.779	0.2	–6.44	243.90	1.729
SBSmk1	1.437	1.170	0.590	39.8	18.97	243.72	1.599
SBSmk2	1.417	1.522	0.150	45.1	27.49	225.98	1.139
SBSmm	1.234	0.666	0.834	25.3	–1.91	242.31	2.515
SBSmw	1.260	0.766	0.844	2.0	–7.20	238.68	1.764
SBSun	1.186	0.628	0.953	2.0	4.71	194.73	0.926
SBSvk	1.312	0.965	0.605	14.7	13.98	243.42	1.828
SBSwk1	1.343	0.933	0.737	12.4	9.68	245.57	1.805
SBSwk2	1.349	1.441	0.103	45.5	34.62	211.02	1.117
SBSwk3	1.342	1.148	0.654	40.3	17.69	222.84	1.296
SWBmk	1.295	1.540	–0.064	42.6	37.92	158.44	1.060
SWBmks	1.279	1.465	0.046	43.5	37.95	141.67	1.102
SWBun	1.143	0.728	0.792	2.0	5.59	151.23	1.227
SWBuns	1.127	0.638	0.874	2.0	3.59	134.49	1.255
SWBvk	0.910	–0.061	1.458	6.1	15.71	145.15	1.034
SWBvks	0.904	–0.062	1.460	2.0	15.91	134.59	0.988

[a] MAT = mean annual temperature; MCMT = mean cold month temperature; TD = summer–winter temperature differential; MAP = mean annual precipitation; MSP = mean summer precipitation; DDGT5 = degree days > 5; and EXT = extreme maximum temperature.

APPENDIX 4 Calculation of relative height (HTp) in the Climate-based Seed Transfer project

Relative height is the expected height of trees from the seed source BEC unit when planted in the plantation BEC unit, relative to the height of trees from a "local" (i.e., plantation) BEC unit seed source. Enter highlighted values into the spreadsheet version of this table (available from the lead author) to calculate the HTp of any seed source growing in any plantation.

Step 1. Convert seed source and plantation BEC unit latitude and 1961–1990 climate variables to standard normal deviates. See Appendix 2 for BEC unit means and standard deviations.

	BEC unit	LAT	MAT	MCMT	TD	MAP	MSP	DDGT5	EXT	log10MAP
Seed source climate (x) (Appendix 2)	BWBSvk	59.525	2.720	−10.109	24.379	1318	428.53	1083.72	30.492	3.120
Plantation climate (x) (Appendix 2)	BWBSwk2	56.896	0.458	−12.225	25.615	566	373.84	884.39	30.088	2.753
Provincial mean ($\bar{x}$)		54.480	1.221	−10.348	23.011	1228	409.33	875.47	30.646	2.971
Provincial standard deviation (sd)		3.338	3.042	5.309	5.292	1089	230.79	371.20	2.850	0.297
$x' = \frac{x - \bar{x}}{\text{sd}}$										
Standaradized seed source climate (x')	BWBSvk	1.511	0.493	0.045	0.258	0.083	0.083	0.561	−0.054	0.501
Standardized plantation climate (x')	BWBSwk2	0.724	−0.251	−0.353	0.492	−0.608	−0.154	0.024	−0.196	−0.734

Step 2. Calculate the Euclidean distance (ED) between the seed source and plantation BEC units using standard normal deviates of climate values of the BEC units. (Only the log transformed version of MAP is used in ED calculation.)

	BEC unit	LAT	MAT	MCMT	TD	MAP	MSP	DDGT5	EXT	log10MAP
Standaradized seed source climate (x')	BWBSvk	1.511	0.493	0.045	0.258	0.083	0.083	0.561	−0.054	0.501
Standardized plantation climate (x')	BWBSwk2	0.724	−0.251	−0.353	0.492	−0.608	−0.154	0.024	−0.196	−0.734
Difference		0.787	0.744	0.399	−0.234	0.691	0.237	0.537	0.142	1.235

$$\text{ED} = \sqrt{d_2^1 + d_2^2 + \cdots + d_n^2}$$

$$\text{ED} = \sqrt{0.787^2 + 0.744^2 + 0.399^2 + -0.234^2 + 0.237^2 + 0.537^2 + 0.142^2 + 1.235^2}$$

ED = 1.8101

Appendix 4 *Continued*

Step 3. Use the half normal transfer function to calculate the relative height (HTp) of a seedlot from the seed source BEC unit growing in the plantation BEC unit. Inputs to the function are two coefficients *(b_0* and b_1), Euclidean transfer distance, and a species-specific 1961–1990 plantation (site) climate variable.

	Site climate variable							
	Species code	**b_0**	**b_1**	**Euclidean distance**	**TD**	**Species code**	**b_0**	**b_1**
	Sx	4.8448	−0.0447	1.8101	25.6151	Pl	2.8742	0.0857
						Sx	4.8448	−0.0447
						Fd	11.56	−0.1671

$$\mathrm{HTp} = e^{\left(\frac{-0.5 \times \mathrm{ED}^2}{e^{\left(b_0 + b_1 \times \mathrm{MAT\_S}\right)}}\right)}$$

$\mathrm{HTp} = 0.9603$

APPENDIX 5 Calculation of relative height (HTp) in the Climate-based Seed Transfer project when assisted migration is used

Relative height is the expected height of trees from the seed source BEC unit when planted in the plantation BEC unit, relative to the height of trees from a "local" (i.e., plantation) BEC unit seed source. Enter highlighted values into the spreadsheet version of this table (available from the lead author) to calculate the HTp of any seed source growing in any plantation.

Step 1. Add migration distance (amount the climate has changed 1945–2034) to 1961–1990 plantation climate to get target plantation climate.

	BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
Migration distance (from Appendix 3)	BWBSwk2	0	1.368	1.656	−0.214	52.5	48.4	190.208	0.85661	
Plantation climate (from Appendix 2)	BWBSwk2	56.896	0.458	−12.225	26.615	566.2	373.8	884.39	30.088	
Migration plantation climate	BWBSwk2	56.896	1.826	−10.569	25.401	618.7	422.3	1074.598	30.94461	2.791511

Step 2. Convert seed source and migrated plantation BEC unit latitude and climate variables to standard normal deviates. See Appendix 2 for BEC unit means and standard deviations.

	BEC unit	**LAT**	**MAT**	**MCMT**	**TD**	**MAP**	**MSP**	**DDGT5**	**EXT**	**log10MAP**
Seed source climate (x) (Appendix 2)	BWBSvk	59.525	2.720	−10.109	24.379	1318.5	428.5	1083.72	30.492	3.120
Migrated plantation climate (x)	BWBSwk2	56.896	1.826	−10.569	25.401	618.7	422.3	1074.60	30.945	2.792
Provincial mean ($\bar{x}$)		54.480	1.221	−10.348	23.011	1228.0	409.3	875.47	30.646	2.971
Provincial standard deviation (sd)		3.338	3.042	5.309	5.292	1089.0	230.8	371.20	2.850	0.297
$x' = \frac{x - \bar{x}}{\text{sd}}$										
Standaradized seed source climate (x')	BWBSvk	1.511	0.493	0.045	0.258	0.083	0.083	0.561	−0.054	0.501
Standardized migrated plantation climate (x')	BWBSwk2	0.724	0.199	−0.042	0.452	−0.559	0.056	0.536	0.105	−0.604

Appendix 5 *Continued*

Step 3. Calculate the Euclidean distance (ED) between the seed source and migrated plantation BEC units using standard normal deviates of climate values of the BEC units. (Only the log transformed version of MAP is used in ED calculations.)

	BEC unit	LAT	MAT	MCMT	TD	MAP	MSP	DDGT5	EXT	log10MAP
Standaradized seed source climate (x')	BWBSvk	1.511	0.493	0.045	0.258	0.083	0.083	0.561	−0.054	0.501
Standardized migrated plantation climate (x')	BWBSwk2	0.724	−0.251	−0.353	0.492	−0.608	−0.154	0.024	−0.196	−0.734
Difference		0.787	0.744	0.399	−0.234	0.691	0.237	0.537	0.142	1.235

$$\mathrm{ED} = \sqrt{d_2^1 + d_2^2 + \cdots + d_n^2}$$

$$\mathrm{ED} = \sqrt{0.787^2 + 0.294^2 + 0.087^2 + -0.193^2 + 0.027^2 + 0.025^2 + -0.159^2 + 1.106^2}$$

ED = 1.4142

Step 4. Use the half normal transfer function to calculate the relative height (HTp) of a seedlot from the seed source BEC unit growing in the plantation BEC unit. Inputs to the function are two coefficients (b_0 and b_1), Euclidean transfer distance, and a species-specific 1961–1990 plantation (site) climate variable.

	Site climate variable							
	Species code	b_0	b_1	**Euclidean distance**	**MAT**	**Species code**	b_0	b_1
	Pl	2.8742	0.0857	1.4142	1.82576	Pl	2.8742	0.0857
						Sx	4.8448	−0.0447
						Fd	11.56	−0.1671

$$\mathrm{HTp} = e^{\left(\frac{-0.5 \times \mathrm{ED}^2}{e^{\left(b_0 + b_1 \times \mathrm{MAT\_S}\right)}}\right)}$$

HTp = 0.9529