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ARTICLE

Methods, Tools, and Technologies

Seedlot Selection Tool and Climate-Smart Restoration Tool: Web-based tools for sourcing seed adapted to future climates

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Abstract

The Seedlot Selection Tool and Climate-Smart Restoration Tool are web-based tools designed to match seedlots with planting sites assuming that seedlots are adapted to the past climates in which they evolved, primarily with respect to temperature and aridity. The tools map the climatic match of seedlots with the past or projected climates of planting sites. The challenge is that future climates are a moving target, which means that seedlots must be adapted to the near-term climates as well as the climates of the mid- to late-21st century. Because climate projections are uncertain, the prudent approach is to aim for the warmest climate that may be expected while ensuring that seedlots moved from warmer to colder locales are not moved so far that they risk cold damage. Uncertainty in climate projections may be mitigated by ensuring genetic diversity through mixing seed sources and having collections from many parents per seed source. Three examples illustrate how to effectively use the web tools: (1) choosing seedlots targeting different future climates for a mid-elevation Douglas-fir site in the Washington Cascades, (2) finding current and future seed sources for restoration of big sagebrush after fires in the Great Basin and Snake River Plain, and (3) planning to ensure that a Douglas-fir seed inventory

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includes seedlots suitable for future climates in western Oregon and Washington.

KEYWORDS
adaptation, assisted gene flow, assisted migration, climate change, climatic transfer distance, genetic variation, reforestation, restoration, seed sourcing

INTRODUCTION

> *I shall endeavor to find out how nature's forces act upon one another, and in what manner the geographic environment exerts its influence on animals and plants. In short, I must find out about the harmony in nature.*
>
> Alexander von Humboldt in letter to Karl Freiesleben, June 1799

Native plant populations are genetically different from one another and are locally adapted to different climatic pressures across the landscape (Alberto et al., 2013; Baughman et al., 2019; Leimu & Fischer, 2008; Linhart & Grant, 1996). As a result, local seed sources are usually recommended for reforestation and restoration. This has typically been accomplished using geographically defined zones or seed transfer rules that limit the geographic or climatic distance that populations from specific locations (also called seed sources) may be moved (Johnson et al., 2004; St.Clair et al., 2020). We now have overwhelming evidence, however, that the climate is warming with an increase in global surface temperature to date of 0.82°C above the 20th century average and a projected future warming of 0.18°C per decade (NOAA, 2021). As the climate changes, the assumption of "local is best" and the use of local seed zones and guidelines may no longer apply (O'Neill & Gómez-Pineda, 2021). Because populations are genetically adapted to their local historical climates, the health and productivity of naturally regenerated or planted ecosystems using native local seed sources will likely decline. Recent observations of increased mortality for many forest tree species in North America can likely be attributed, at least in part, to changes in climate (Allen et al., 2010, 2015; Sáenz-Romero et al., 2020; van Mantgem et al., 2009). Impacts due to climate change will likely only get worse—the amount of climate change to date is small compared to what is projected for the rest of the century (McDowell et al., 2016, 2020; NOAA, 2021).

Natural resource managers may respond to concerns of maladaptation and declines in ecosystem productivity by matching the climate to which their plant material is adapted to the projected climatic conditions of their reforestation or restoration sites. The human-assisted movement of species or populations to areas outside of their recent historical distributions to maintain biological diversity or ecosystem function in response to climate change is known as assisted migration (Pedlar et al., 2012; D. M. Richardson et al., 2009; Schwartz et al., 2012). More specifically, the movement of populations or seed sources to areas with suitable future climates is referred to as assisted population movement or assisted gene flow when done within the recent historical range of the species, or referred to as assisted range expansion when done just beyond its recent historical range (Aitken & Whitlock, 2013; M. I. Williams & Dumroese, 2013). Nearly 30 years ago, Ledig and Kitzmiller (1992) proposed that reforestation programs would need to respond to concerns of climate change by emphasizing "conservation, diversification, and broader deployment of species, seed sources, and families," specifically stating that "planting programs may have to deploy non-local seed sources, imported from further south or lower elevations." Since then, climate-interpolation models (Rehfeldt, 2006; Wang et al., 2016) have been developed that enable resource managers to more accurately estimate the climate at specific locations to guide population movement based on climate rather than geography. And although climate projections remain uncertain, what is certain is that our climate is getting warmer. It is just a matter of how quickly we get there.

We developed two web-based tools to facilitate matching the climates of seed sources to the climates of reforestation or restoration sites. In that regard, both tools are simply climate mapping tools. They are based on the premise that plant populations have a climatic niche in which they best survive, grow, and reproduce, and that plant populations are best adapted to the locations in which they evolved (i.e., exhibit local adaptation). The tools assume that the user has prior knowledge of the relationship between climate and adaptive genetic variation across the landscape. In its simplest form, that knowledge may just be the assumption that plant populations are adapted to differences in temperature and aridity. However, the tools also have the capability to incorporate genetic information from common garden studies of the functional relationship between adaptive traits and multivariate climate variables (called genecology studies). The tools allow the option to map both seedlots and planting sites simultaneously, enabling resource managers to best evaluate climatic similarity between them. The tools are flexible, allowing users to explore different assumptions about the relationships between adaptation and climate including how the climate changes over time. Thus, the tools may help users evaluate potential maladaptation from a warming climate and guide-assisted migration options to respond to concerns given different assumptions.

The two tools use a similar approach and user interface. The primary difference between them is that one tool, the Seedlot Selection Tool (SST; website: https://seedlotselectiontool.org/sst/), is oriented toward trees, whereas the other tool, the Climate-Smart Restoration Tool (CSRT; website: https://climaterestorationtool.org/csrt/), is oriented toward non-tree native species commonly used in restoration. Two tools oriented to different audiences will make it easier for users to find information with respect to seed and breeding zones and species-specific functions as more species-specific information is incorporated into the tools. The objective of this paper is to describe the methodology behind these tools for sourcing seed adapted to current as well as future climates including a description of the theoretical basis, the inherent assumptions, and a detailed account of the inputs and outputs. We then present three examples to illustrate tool features, use, interpretation, and general conclusions for successful assisted migration in the Pacific Northwest and Great Basin regions of the United States.

METHODOLOGY

Theoretical basis and assumptions

The SST and CSRT are based on the premise that all plants populations have a climate in which they have the greatest fitness and can best survive, grow, and reproduce. The objectives of the tools are to map the climate of greatest fitness based on assumptions of how seedlots from native populations are adapted to the source climates in which they evolved.

The first assumption is that populations are locally adapted with respect to climate; that is, populations with the highest fitness at a site in which they are growing come from locations that have a similar climate. Evidence for local adaptation comes from reciprocal-transplant studies in which populations from different source environments are planted back into a common garden at each of those environments (Kawecki & Ebert, 2004). Reviews of local adaptation are primarily from herbaceous species and indicate that local adaptation is common, although may vary based on the characteristics of the taxa and population size (Baughman et al., 2019; Hereford, 2009; Leimu & Fischer, 2008). In forest trees, provenance tests with many populations sampling a wide range of environments may approximate reciprocal-transplant studies and allow evaluation of local adaptation as a function of the climatic or geographic transfer distance between seed sources and planting sites. Although results from long-term tests using adequate numbers of populations and test sites tested over a large climatic range are few, studies indicate that forest trees are, in general, locally adapted, except perhaps at the northern margins of the species ranges where they may show adaptive lag (Rehfeldt et al., 1999; Savolainen et al., 2007; St.Clair et al., 2020; Wang et al., 2006).

The second assumption is that genetic variation among plant populations in adaptation and adaptive traits is related to climate as observed in more than 200 years of common garden studies, and that most variation is continuous along climatic gradients, that is, clinal rather than discreet or ecotypic (reviewed by Aitken & Bemmels, 2015). The tools allow users to select among 16 climate variables to be mapped that reflect different climatic factors of temperature and aridity (Table 1). In general, genetic studies indicate that adaptation in temperate forest trees is most strongly related to cold temperatures in the winter and aridity during the growing season (Aitken & Bemmels, 2015). That is likely to be true of other perennial plant species as well. For that reason, the tools have the option for the user to automatically choose default climate variables of mean cold month temperature (MCMT) and the ratio of summer temperatures to summer precipitation (SHM).

The third assumption associated with clinal variation is that fitness gradually decreases as climatic transfer distances (CTDs) increase, leading to lower survival, growth, and plant stand productivity. Furthermore, some species may be considered generalists with respect to the breadth of climates in which populations thrive, whereas other species may be considered specialists with a much narrower population niche (Rehfeldt, 1994). The tools allow users to specify a CTD that reflects differences among species in the breadth of population niches as well as the risk in decreased productivity that they are willing to accept. This is defined in the tools as the climatic transfer limit (TL). Climatic TLs may be based on knowledge from long-term genetic tests, or on practical experience from the use of seed zones or breeding zones, or seed transfer guidelines.

Programming languages and data sources

The tools each consist of three components: a core back-end component and core user interface component that

TABLE 1 Climate variables in the Seedlot Selection Tool and Climate-Smart Restoration Tool available for characterizing the adaptation of seedlots, the past and future climates of planting sites, and their climatic match

Climate variable	Definition	Units
MAT	Mean annual temperature	°C or °F
MCMT	Mean coldest month temperature	°C or °F
MWMT	Mean warmest month temperature	°C or °F
EMT	Extreme minimum temperature over 30 years	°C or °F
EXT	Extreme maximum temperature over 30 years	°C or °F
FFP	Frost-free period	days
DD < 0	Degree-days below 0°C, chilling degree-days	degree-days
DD > 5	Degree-days above 5°C, growing degree-days	degree-days
TD	Temperature difference between MWMT and MCMT, or continentality	°C or °F
MAP	Mean annual precipitation	mm or inches
MSP	May to September precipitation	mm or inches
AHM	Annual heat-moisture index [(MAT + 10)/(MAP/1000)]	ratio
SHM	Summer heat-moisture index [(MWMT)/(MSP/1000)]	ratio
CMD	Hargreaves climatic moisture deficit	mm or inches
Eref	Hargreaves reference evaporation	mm or inches
PAS	Precipitation as snow, August to July	mm or inches

Note: Climate variables are as defined and derived in ClimateNA v5.30 (Wang et al., 2016).

make up the shared codebase between the SST and CSRT and a third component consisting of tool-specific settings, labels, styles, and functionality. The core backend component is written in the Python programming language. It calculates climatic distances and handles other data-related requests and processing. The core user interface component is written in JavaScript and TypeScript, and handles all visualization and user interaction for the tools.

The SST and CSRT use climate values derived from ClimateNA v5.30 (Wang et al., 2016; http://climatena.ca). ClimateNA is a user-friendly application that extracts and downscales monthly climate data layers for temperature and precipitation for the normal period of 1961–1990 from moderate spatial resolution (4 × 4 km) to scale-free point estimates for the continent of North America (Wang et al., 2016). Downscaling is achieved through a combination of bilinear interpolation and dynamic local elevational adjustment. ClimateNA then uses the derived data as a baseline to determine historical and future climate variables for individual years and periods between 1901 and 2100. ClimateNA also calculates a number of biologically relevant climate variables from the temperature and precipitation data. From the ClimateNA data, we created a gridded surface map of North America using a USGS DEM at a resolution of 15 arc seconds (~450 m; https://topotools.cr.usgs.gov/GMTED_viewer/viewer.htm) for two historical climate normals (1961–1990 and 1981–2010) and three future climate normals (2011–2040, 2041–2070, and 2071–2100) for the 16 temperature- and aridity-related variables.

For the future projections, we used an ensemble of results from 15 climate models. The climate models were derived from the Coupled Model Intercomparison Project phase 5 database of the 5th IPCC Assessment Report (IPCC AR5 WGI, 2013). Climate projections are driven by assumptions about future greenhouse gas concentrations based on simulated land use change and economic development as represented by a set of Representative Concentration Pathways (RCPs) (Moss et al., 2010). The SST and CSRT use both RCP 4.5 and RCP 8.5, with each number reflecting the additional radiative forcing by 2100 compared to that of pre-industrial times (2.5 W m^{-2}). Radiative forcing (in watts per square meter) quantifies the combined effect of greenhouse-gas emissions and other factors such as atmospheric aerosol levels on the earth's climate (Hausfather & Peters, 2020). RCP 4.5 is a scenario that assumes the imposition of emissions mitigation policies with global emissions peaking around 2040 and remaining stable afterwards. Its radiative forcing reaches a peak of ~4.5 W m^{-2} with a concentration of ~650 ppm CO_2-eq. causing a mean projected increase in global mean annual temperature of 1.8°C by 2100 (range = 1.1–2.6°C) relative to the period 1986–2005 that remains stable afterwards (IPCC AR5 WGI, 2013; Moss et al., 2010). RCP 8.5 is often described as a worst-case scenario with global emissions continuing to rise throughout the 21st century causing a peak radiative forcing of ~8.5 W m^{-2} and a CO_2-eq. concentration of ~1370 ppm by 2100 relative to 1986–2005. In this scenario, global mean annual temperature is projected to reach 3.7°C by the end of the century (range = 2.6–

4.8°C) and to continue to rise beyond 2100 (IPCC AR5 WGI, 2013; Moss et al., 2010). The high-end scenarios RCP 8.5 from AR5 (IPCC AR5 WGI, 2013), and especially the more dire SSP5-8.5 from AR6 (IPCC AR6 WGI, 2021), have been argued to be unlikely to happen (Hausfather & Peters, 2020). However, from 2006 to 2014, the first years of RCP 8.5-driven transient projections, simulated emissions were so close to those observed that they were used to fill data gaps in regional assessments (IPCC AR6 WGI, 2021), Furthermore, RCP 8.5 projections are highly likely to match projections to at least mid-century given current policies (Schwalm et al., 2020). RCP 8.5 highlights the risks that might emerge from extreme conditions, a useful exercise to prepare for such occurrences. Indeed, our projections using RCP 8.5 and an ensemble of the average projections of 15 climate models do not include the results from the most extreme single models. Our purpose in providing alternative climate periods and RCPs from which to choose is not to state with certainty if or when those future conditions might occur, but instead to allow users to explore alternative climate scenarios for choosing seedlots or planting sites for future climates. The risk of maladaptation should be acceptable to the user if they select seed sources adapted to the near-term climate (within their climatic TL) as well as matched to the worst-case scenario (i.e., with a CTD of zero).

Input steps

Both the SST and CSRT involve seven steps for choosing objectives and indicating how plant populations are adapted to climate (Figure 1): (1) choose the mapping objective, (2) identify a planting site or seedlot location, (3) identify the mapping region, (4) select time periods for adaptation of seedlots to planting sites, (5) choose a method for defining TLs, (6) define climate variables to be mapped and TLs, and (7) apply constraints to limit the geographic extent of results.

The first step is to choose the mapping objective. The user may either search for suitable seedlots given the location of a planting site or search for suitable planting sites given the location of a seedlot. For example, given a warmer future climate, the objective of mapping seedlots for a planting site would indicate where one would find seedlots that originate from warmer locations and would be better adapted to planting sites that are expected to be warmer in the future. The objective of mapping suitable

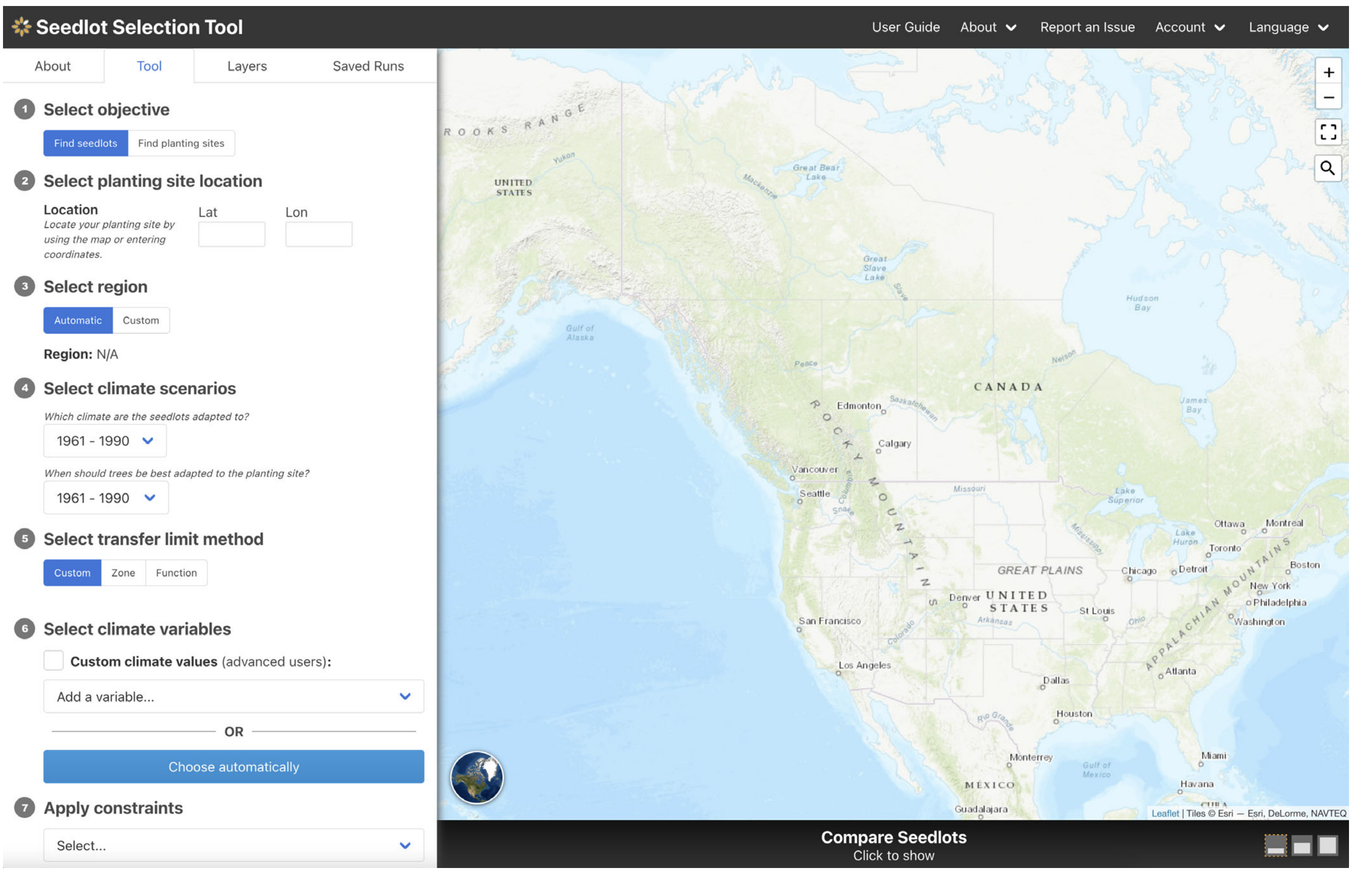

FIGURE 1 User interface of the Seedlot Selection Tool showing the seven steps for inputting information

planting sites for a seedlot would indicate where one would find planting sites that are expected to be warmer in the future for a seedlot that is pre-adapted to warmer conditions (i.e., climate matched).

The second step is to select the location of the planting site or seedlot given the objective specified in Step 1. Locations may be selected by providing geographic coordinates or by clicking on the map.

The third step is to identify the region in which to map the results. The geographic extent of the tools is North America including Canada, the United States, and Mexico. North America is divided into seven overlapping regions to reduce processing time. The tools will automatically choose the region with the center point closest to the location provided in Step 2. Users can override this default region to map results to a different region by choosing the region of interest in Step 3.

The fourth step is to select the time periods for mapping the climatic similarity of the seedlot and planting site. Users choose two time periods: the past time period to which seedlots are adapted and the past or future time period in which plants grown from those seedlots are expected to be suitable to the climate at a planting site. The time period to which seedlots are adapted is typically assumed to be the past climate having the greatest influence on the inherited traits that confer survival, growth, and reproduction of the seedlot's parents. Although adaptation may result from natural selection over generations, one may assume that the adaptation period may be represented by the 1961–1990 climate normal, a period prior to appreciable warming trends. For shorter-lived species with greater potential to respond to natural selection, users can use the 1981–2010 climate normal. Future time periods in which plants should be suitable to a planting site are represented by the three climate normals of the next few decades (2011–2040), the mid-century (2041–2070), or late-century (2071–2100). The tools also offer the option to map suitability to past climates to explore the climatic similarity of seedlots and planting sites prior to changes in climate.

The method used to choose TLs for climate variables is chosen in Step 5, followed by choosing the climate variables of interest in Step 6. TLs may be adjusted after choosing the climate variables. The climate variables and associated TLs reflect the adaptive capacity of the seedlots and form the basis of mapping climatic similarity within the tools.

Three alternative approaches are used to determine TLs: Custom, Zone, and Function. The Custom and Zone approaches allow user-defined TLs for each climate variable selected in Step 6. TLs for the Custom approach may be selected based on the experience of the user and the best available science. The tools provide an option to automatically select MCMT and SHM and calculate default TLs of ±2.0°C for MCMT and plus or minus half of the value at location of the planting site or seedlot specified in Step 2 for SHM. The Zone approach differs from the Custom approach by suggesting a TL based on the range of climatic conditions within the zone of the planting site or seedlot. The idea is that the user would feel comfortable with the TL given that resource managers have been operationally moving populations within the zone since zones were established more than a half century ago. The TL is calculated for a specific zone for each climate variable as: $\mathrm{TL} = (x_{\max} - x_{\min})/2$, where $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the climate variable for that zone. The assumption is that half the range of the climate variable values represents a "typical" past transfer. However, the range of climates within zones can vary substantially from one zone to another. For example, although the average TL for all the 1966/1973 Oregon and Washington tree seed zones (where zone is defined as the elevation band within the broader geographic delineation shown on seed zone maps) for mean temperature in the coldest month is 0.85°C, the values may differ among zones from near zero to 3.05°C. For that reason, the tools also indicate the average TLs for all zones within a selected zone set (where zone set is defined as the collection of zones commonly used for a given geographic region). Using that or other information, the TL may be modified by the user. In both the Custom and Zone approaches, the TLs may also be adjusted based on the user's level of acceptable risk.

The Function approach uses a genecological function that is typically derived from genetic research. Genecological functions use climate or other environmental variables to explain trait variation (e.g., growth, cold hardiness, or phenology) observed in common garden trials. More specifically, genecological functions are associations between adaptive traits and the climate at seed-source locations. Values using the Function approach are given as trait differences that are representative of climatic differences; that is, the trait value at a location is the expression of the intercept and slopes defined by one or more location-specific climate variables. The seed TLs are determined from the confidence intervals calculated from the genecology function (B. A. Richardson & Chaney, 2018). The TLs using the Function approach cannot be modified by the user. Future versions of the SST and CSRT are planned to include the option for users to use their own functions that allow climate variables to be assigned different weights.

The last step before mapping results is the option to apply constraints to the mapped output. Users have a choice among geographic constraints including latitude, longitude, elevation, distance, photoperiod, or species range. Species ranges include a list of results from species distribution models (SDMs) for contemporary climates when looking for seedlots for a planting site, or for contemporary or future climates when looking for planting sites for a seedlot. Users also have the option to import their own geographic boundary to use as a constraint. Using constraints will exclude that part of the climatic output that is beyond the geographic limits imposed or beyond the species range.

Output

Both tools produce a map that shows where a land manager may find appropriate seedlots or planting sites for the location specified in Step 2 based on the climate of the time periods specified in Step 4 using the climate variables and TLs specified in Step 6. The map shows the degree of match between the past climate to which a seedlot is adapted and the climate of the time period to which the plants are expected to be best adapted to the restoration or reforestation site (Figure 2). The darkest orange indicates the best match and the lightest orange indicates the match that is at the edge of the TL. Although the specific TL affects the extent of the mapped area of suitability, it does not affect the locations of the best matches, which is equal to a CTD of zero (equal to planting-site climate minus seed-source climate).

The first step in producing a map is to exclude all grid points that lie outside of the TLs for the climate variables chosen in Step 6. Next, the degree of match between seedlot and planting site is calculated for each remaining grid point by rescaling the gridded data for each climate variable, or associated trait from a genecology function, as: $y_{ij} = |x_{ij} - x_{i(\mathrm{mid})}|/\mathrm{TL}_i$, where y_{ij} is the rescaled value and x_{ij} is the original value for the ith climate variable and jth grid point, $x_{i(\mathrm{mid})}$ is the midpoint value (or climatic center) and TL_i is the default or user supplied TL for the ith climate variable (specified in Step 2). Second, the scaled multivariate climatic distance (d) from the climatic center to each grid point is calculated as the Euclidean distance for i climate variables: d = square root $(y_{1j}{}^2 + y_{2j}{}^2 + \ldots + y_{ij}{}^2)$. Finally, the relative climate match (m) is calculated as $m = 100 - d \times 100$. Values between 0 and 100 are mapped using the color scale ranging from light to dark orange. Note that the Euclidian distance for a single climate variable is simply the absolute value of the difference between the climate of the seedlot and the planting site.

The SST and CSRT can compare multiple seedlots to a planting site, or multiple planting sites to a seedlot, using the climate-match mapped output as a backdrop. This allows the user to evaluate and prioritize an inventory of seedlots for a specific planting site, or to evaluate and prioritize a list of planting sites for a specific seedlot. The output includes a table of the selected seedlots or planting sites, the climate match (m), and the CTD for each climate variable.

CASE STUDIES

We illustrated the utility of the SST and CSRT using three case studies for the western United States. The western United States is an interesting region to consider given that it is an area of high topographic relief resulting in high climatic, species, and genetic diversity across relatively narrow geographic areas. The three case studies included:

1. Using the SST to find suitable Douglas-fir seedlots for reforestation of a site at a mid-elevation in the central Washington Cascades.
2. Using the CSRT to find suitable locations for collecting Wyoming big sagebrush for restoration of burned areas in the Great Basin and Snake River Plain.
3. Using the SST to do a gap analysis to determine how well seedlots from Douglas-fir seed orchards of the US Forest Service Pacific Northwest Region meet the needs for future reforestation in western Oregon and Washington given concerns about climate change.

Case study 1: Suitable Douglas-fir seedlots for reforestation at a site in the central Washington Cascades

Douglas-fir (*Psuedotsuga menziseii*) is an important part of reforestation programs in the Pacific Northwest of the United States and Canada. Douglas-fir is valued both for its structural wood properties as well as the ecosystem services it provides. Wildfires will lead to an increase in reforestation needs. Although devastating, wildfires, as well as timber harvests, could present an opportunity to replace future maladapted forest stands with trees better adapted to a warmer climate 30–50 years from now. Hopefully, once established, future forest stands will be resistant to changes beyond 50 years.

We considered reforestation of a mid-elevation site in the west-side of the central Washington Cascades. The previous stand was a 45-year-old Douglas-fir/western hemlock stand located at latitude 46.582 north, longitude −121.913 west at an elevation of 670 m on mostly flat ground in the Gifford Pinchot National Forest. The local USFS breeding zone was Zone 03012 with an elevation

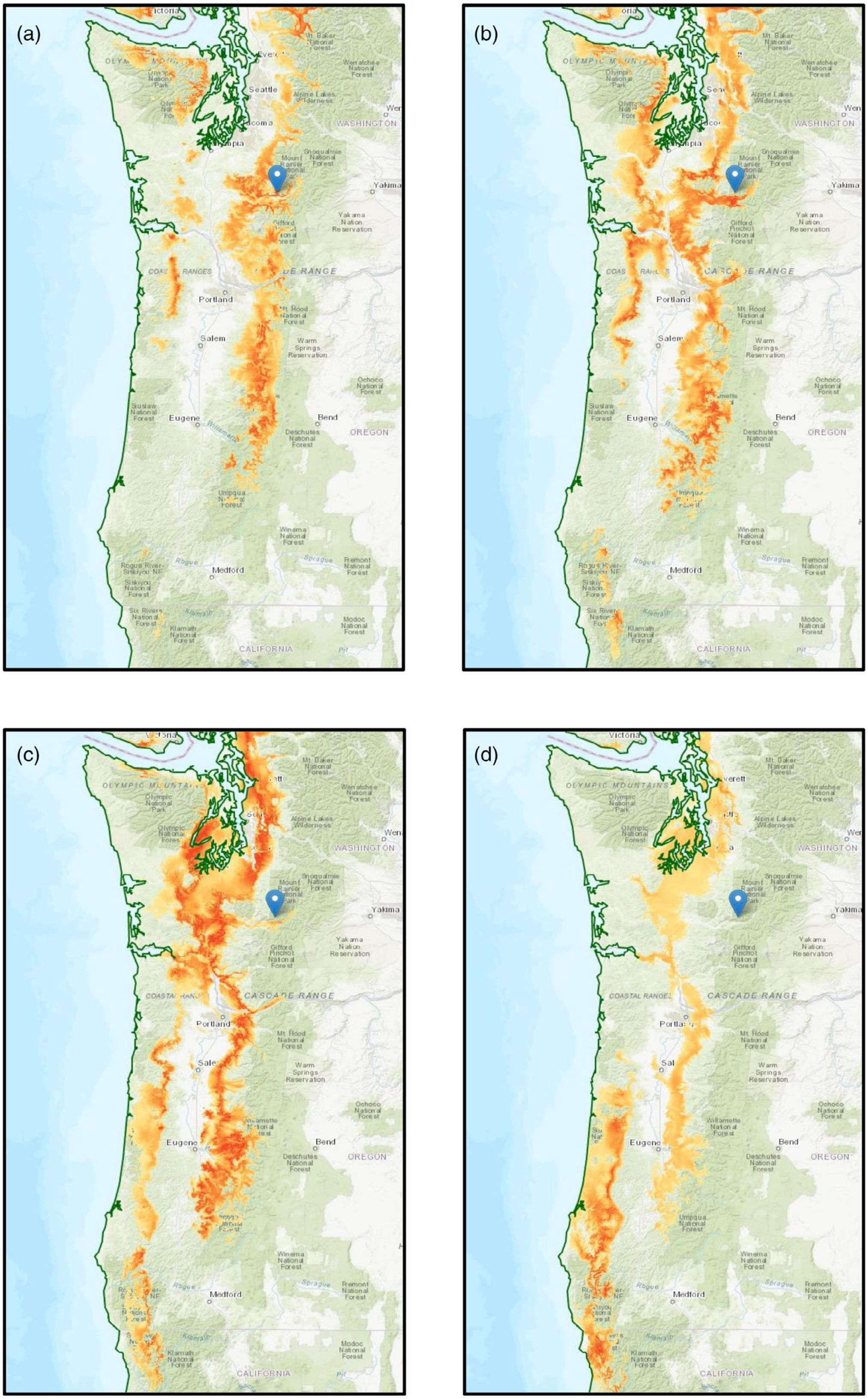

FIGURE 2 Screenshots of the Seedlot Selection Tool showing Douglas-fir seed sources adapted to a planting site in the central Washington Cascades as indicated by the climatic match with the climates of (a) 1961–1990 and projected climate change from 1961–1990 to (b) 2011–2040 RCP 8.5, (c) 2041–2070 RCP 8.5, and (d) 2011–2040 RCP 8.5

band of 1501–2500 ft (1 foot = 0.3048 m). The objective of reforestation was to set up an assisted migration trial using standard operational planting procedures. Four seedlots were considered for the trial, including a control based on a local seedlot adapted to historical climate conditions (i.e., ignoring climate change) and seedlots chosen to be adapted to three different future time periods. The seedlots came from Douglas-fir collections set up to supply seed for reforestation programs in the National Forests of the USFS Pacific Northwest Region (Region 6). All four seedlots were from seed collected in seed orchards. The seedlots were assumed to be representative of the zones from which the parents in the seed orchard came since parents were assumed to have had little selection pressure applied and came from throughout the zones.

The climate of the planting site was projected to continue to get warmer (Table 2) with a projected increase of 1.2–1.9°C warmer (depending on the season and assumed RCP) for 2011–2040 compared to the 1961–1990 climate normal. Although recent-past and near-term warming was within the climatic TL of about 2.0°C for different temperature variables, warming by mid-century will exceed those TLs. Thus, we might expect to see decreased productivity and increased mortality as a consequence of maladaptation. By the late 21st century, warming was projected to be considerable, as high as 2.7–6.3°C depending on the temperature variable chosen and assumed RCP. Warming was projected to be greater in the summer than in the winter. Thus, climates were projected to become more continental and less maritime as measured by the difference between summer and winter temperatures (TD). Mean annual precipitation was projected to slightly increase (less than 5%). Summer precipitation was projected to decrease. Increasing summer temperatures and decreasing summer precipitation will lead to more arid summers as measured by the summer heat: moisture index (SHM).

Assumptions about RCPs were not critical in the near-term. The difference in temperature between RCP 4.5 and RCP 8.5 was minor for the 2011–2040 climate normal (Table 2). By mid-century, however, differences started to become larger, and were quite large by late-century (up to 2.6°C difference between RCP 4.5 and RCP 8.5 for mean temperature of the warmest month). Temperature projections for the mid-century using RCP 8.5 were similar to those of the late-century using RCP 4.5. It may be prudent to assume a worst-case scenario of RCP 8.5 toward the end of the century, but not move populations too far from a warm to cold climate leading to a higher risk of cold damage. That way if the climate does not change as quickly as projected, populations may be adapted further into the future in addition to being adapted to the near-term.

The climate variables we used for looking for seedlots adapted to the planting site for the proposed assisted migration trial were MCMT and SHM. We did not consider changes in continentality (i.e., TD) because continentality was expected to increase (become less maritime), and, thus, was not a concern for *Rhabdocline* needle cast disease which can be a problem for continental seed sources growing in maritime climates (Wilhelmi et al., 2017). We then considered the climatic match between the climate of the three future time periods and the climate of the seedlots in the seed inventory assuming the seedlots were adapted to the climate of 1961–1990. The climatic TLs chosen to limit the mapped output of the climatic match were the default values of 2.0°C for MCMT and 23.8 for SHM. We assumed RCP 8.5 for future scenarios. Results for future time periods as well as the past (i.e., ignoring climate change) are given in

TABLE 2 Past and future 30-year climate normals and amount of climate change (in parentheses) for select temperature and aridity variables for a planting site located in the central Washington Cascades

Time period and future RCPs	MAT (°C)	MCMT (°C)	MWMT (°C)	TD (°C)	MAP (mm)	MSP (mm)	SHM (ratio)
1961–1990	8.0	0.7	16.4	15.7	1833	349	47.0
1981–2010	8.2 (+0.2)	1.4 (+0.7)	16.7 (+0.3)	15.3 (−0.4)	1844 (+11)	339 (−10)	49.2 (+2.2)
2011–2040 RCP 4.5	9.3 (+1.3)	1.9 (+1.2)	18.1 (+1.7)	16.2 (+0.5)	1848 (+15)	320 (−29)	56.6 (+9.6)
2011–2040 RCP 8.5	9.4 (+1.4)	2.1 (+1.4)	18.3 (+1.9)	16.2 (+0.5)	1829 (−4)	317 (−32)	57.8 (+10.8)
2041–2070 RCP 4.5	10.2 (+2.2)	2.9 (+2.2)	19.4 (+3.0)	16.5 (+0.8)	1855 (+22)	310 (−39)	62.4 (+15.4)
2041–2070 RCP 8.5	10.9 (+2.9)	3.3 (+2.6)	20.3 (+3.9)	16.9 (+1.2)	1884 (+51)	303 (−46)	67.0 (+20.0)
2071–2100 RCP 4.5	10.8 (+2.8)	3.4 (+2.7)	20.1 (+3.7)	16.8 (+1.1)	1885 (+52)	306 (−43)	65.9 (+18.9)
2071–2100 RCP 8.5	12.6 (+4.6)	5.0 (+4.3)	22.7 (+6.3)	17.8 (+2.1)	1920 (+87)	298 (−51)	76.4 (+29.4)

Note: The planting site is located at latitude 46.582, longitude −121.913, elevation 669 m on the Gifford Pinchot National Forest.
Abbreviations: MAP, mean annual precipitation; MAT, mean annual temperature; MCMT, mean coldest month temperature; MSP, May to September precipitation; MWMT, mean warmest month temperature; RCP, Representative Concentration Pathway; SHM, summer heat-moisture index [(MWMT)/(MSP/1000)]; TD, temperature difference between MWMT and MCMT, or continentality.

Figure 2. The map indicates that seedlots adapted to the future climate at the planting site in the Gifford Pinchot National Forest were generally found nearby at lower elevations in the Puget Trough or further south. If limiting the choice of seedlots to those in the National Forests inventory, one would look for seedlots from the lower elevations of the nearby seed zone (03011 elevation 501–1000 ft) for seedlots adapted to the near-term climate (2011–2040). Seedlots adapted to the mid-century climate were located further south on the Willamette or Umpqua National Forests. Seedlots adapted to the late-century climate were located as far south as the Siuslaw or Siskiyou National Forests or the National Forests of northwest California.

We next determined the CTDs for MCMT and SHM for each candidate seedlot from the different National Forests (Table 3). We limited the seedlots to those from seed orchards to avoid comparisons of different types of seed collections. To characterize the climate of the seed orchard seedlots, we used the climatic center of the zones. For each time period, we chose the orchard seedlot with a CTD for MCMT near zero for the time period, but with a CTD for SHM that was within the TL of ±23.5. The seedlot from the local zone was adapted to the near-term climate (i.e., within the TLs for MCMT and SHM for 2011–2040), but maladapted to warmer climates by mid-century (CTD = 2.6°C for MCMT) and drier climates by late-century (CTD = 24.7 for SHM). The seedlot from a nearby lower elevation (zone 03011 elevation 501–1500 ft) was adapted to the near-term climate (CTD = 0.3°C) and mid-century climate (CTD = 1.5°C), but maladapted by late-century (CTD = 3.2°C). The seedlot from a much warmer climate of the Siuslaw National Forest (zone 12031 elevation 1–1000 ft) was maladapted to the near-term climate (CTD = −2.9°C). We concluded that the best seedlot would be from the Willamette National Forest (zone 18011 elevation 1001–2000 ft), which had a CTD of −0.1°C for the mid-century climate but was still within a TL for MCMT of 2.0°C for the near-term climate (CTD = −1.3°C). It was also within the TL for MCMT for the late-century climate (CTD = 1.7°C).

Case study 2: Available seedlots for restoring big sagebrush after wildfires

Changes in climate can bring about range shifts as has been documented in the paleo record (J. W. Williams et al., 2004) and projected in many studies using SDMs (Rehfeldt et al., 2006; Shirk et al., 2018). However, SDMs generally do not consider adaptive genetic variation in their predictions for future climates, and therefore, may overestimate the fundamental niche. This is especially true if climate change outpaces gene flow as is likely happening (Jump & Peñuelas, 2005). For species to realize their future climate niche projection, assisted population migration will likely be needed from the appropriate seed sources. Populations in the current trailing edge of a species range will be critical for buffering further maladaptation to the mid-century climate, but these populations are likely those that are most threatened by range contraction. Therefore, current restoration planning will need to consider seed sources from trailing-edge populations, either through seed banks or seed orchards, to maintain some areas of the species niche that are predicted to remain stable.

In the case study below, we used random locations within 13 recent wildfires to map seed sources of Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*) that are suitable for restoration of the wildfire sites (Table 4). We used the Function option in Step 5 to map the trait values for each grid point in the map based on the genecology functions for two adaptive traits: flowering date and survival. The locations of suitable seed sources were constrained by the TLs based on confidence intervals of each function (Chaney et al., 2017; B. A. Richardson et al., 2017; B. A.

TABLE 3 Climatic transfer distances of seedlots from four Douglas-fir seed orchards to the past and future climates of the planting site located in the central Washington Cascades

	Adapted to		Climatic transfer distance for MCMT (°C)				Climatic transfer distance for SHM (ratio)			
Seedlot	MCMT (°C)	SHM (ratio)	1961–1990	2011–2040	2041–2070	2071–2100	1961–1990	2011–2040	2041–2070	2071–2100
BZ 03012 (1501–2500)	0.7	51.7	+0.0	+1.4	+2.6	+4.3	−4.7	+6.1	+15.3	+24.7
BZ 03011 (501–1500)	1.8	60.4	−1.1	+0.3	+1.5	+3.2	−13.4	−2.6	+6.6	+16.0
BZ 18011 (1001–2000)	3.4	80.4	−2.7	−1.3	−0.1	+1.6	−33.4	−22.6	−13.4	−4.0
BZ 12031 (1–1000)	5.0	594	−4.3	−2.9	−1.7	0.0	−12.4	−1.6	+7.6	+17.0

Note: Climatic transfer distance calculated as the past or future climate of the planting site minus the climate to which the seedlot is adapted (assumed to be 1961–1990). Future climates assume RCP 8.5 and are given in Table 2. Ranges in parentheses following the seedlot IDs are elevation bands in meters.

TABLE 4 Nearest seed sources and seed transfer area for restoration of Wyoming big sagebrush habitat adapted to a mid-century climate for locations within 13 large wildfires in the interior western United States

					Seed transfer area (km^2)	
Wildfire	**Lat**	**Long**	**Elev (m)**	**Nearest seed source**	**Current**	**Mid-century**
Buzzard	43.322	−118.223	1422	Descend 250 m	141,185	26,091 (81%)
Cinder	43.535	−119.892	1435	50 km	155,440	57,625 (63%)
Clay	39.424	−112.294	1580	80 km	107,135	0 (100%)
Davis	40.168	−112.606	1712	Descend 215 m	139,807	10 (99%)
Dry Gulch	41.789	−114.330	1779	50 km	341,318	25,951 (92%)
Hot Pot	41.117	−116.961	1409	50 km	322,321	9051 (97%)
Long draw	42.635	−117.657	1256	150 km	210,130	7015 (97%)
Martin	41.571	−116.82	1633	Descend 275 m	196,526	14,547 (93%)
Pothole	42.63	−115.60	1193	Descend 300 m	224,308	5467 (98%)
Powerline	42.737	−112.635	1462	100 km	302,105	6009 (98%)
Preacher	43.169	−114.046	1387	150 km	193,526	3678 (98%)
Sheep	43.626	−112.813	1493	200 km	147,830	2 (99%)
Soda	43.381	−116.864	1252	Descend 400 m	204,975	12,823 (93%)

Note: The nearest seed source shows the approximate geographic distance if >50 km or elevation if <50 km to collect seed for mid-century climate. The area of seed sources suitable to the current climate (in square kilometers) are calculated for each focal point and constrained by the current Wyoming big sagebrush species distribution model (SDM). The areas of seed sources suitable to mid-century climate (in square kilometers) are constrained by the mid-century SDM (combined RCP 4.5 and 8.5). The percent loss in area is shown in parentheses.

Richardson & Chaney, 2018). The mean trait values and TLs are given in Step 6 of the CSRT. The map of suitable seed sources for each restoration site is then determined based on the Euclidian distance of the two traits. The CSRT then constrains the map of suitable seed sources by the SDM (adapted from Still & Richardson, 2015) to limit the seed transfer projection to within the species range. These SDM constraints are applied in Step 7 of the CSRT procedure. To illustrate the dilemma resource managers could face in the upcoming decades, we compare locations of suitable seed sources for contemporary (1981–2010) and mid-century climates (2041–2070 RCP 8.5). Gridded maps of the suitable seed-source areas for each wildfire site were exported from the CSRT to ArcMap v.10 (ESRI) and examined for the two time periods using spatial overlap with the Raster program of the R statistical platform (Table 4).

Land managers will face many difficult restoration decisions over the next few decades. One important question is: what seed sources can replace existing local maladapted sources as the climate warms in the mid-century? Our analysis of 13 wildfire sites in Wyoming big sagebrush habitat indicated that suitable seed-sources areas are projected to shift and contract substantially between now and mid-century, leading to maladaptation of the current local seed source. The geographic distance required to obtain seed sources adapted to the mid-century depended primarily on local topography. In areas with high topographic relief, seed sources were typically available within 50 km of the restoration site but required descending in elevation between 200 and 400 m (Figure 3a, Table 4). In areas of low topographic relief, geographic distances required to obtain mid-century adapted seed increased from 50 to 250 km (Figure 3b, Table 4).

If not proactively addressed in the near-term through seed banking or seed orchards, climate-caused species range shifts could affect seed availability in the future, especially among trailing-edge populations, as illustrated for the 13 recent wildfire sites. Overlaying suitable seed sources and the SDMs for current climates and mid-century projections (RCP 8.5) revealed that 93% of the area of suitable seed sources were in areas of range contraction (Table 4). This loss is illustrated in the mapped seed sources for the Soda and Preacher wildfires (Figure 3). Using the overlays of suitable seed source areas and SDMs, the maps show a predicted dramatic loss of suitable seed-source area by mid-century. This loss is driven by the need to match restoration sites with warm-adapted seed collections. However, these warmer seed source areas, typically located at the trailing edge of the species range, are vulnerable to range contraction. Suitable seed sources are reduced to small areas by mid-century (orange cross-hatched areas in Figure 3), equating to an estimated loss of 98% for the Preacher wildfire and 93% for the Soda wildfire.

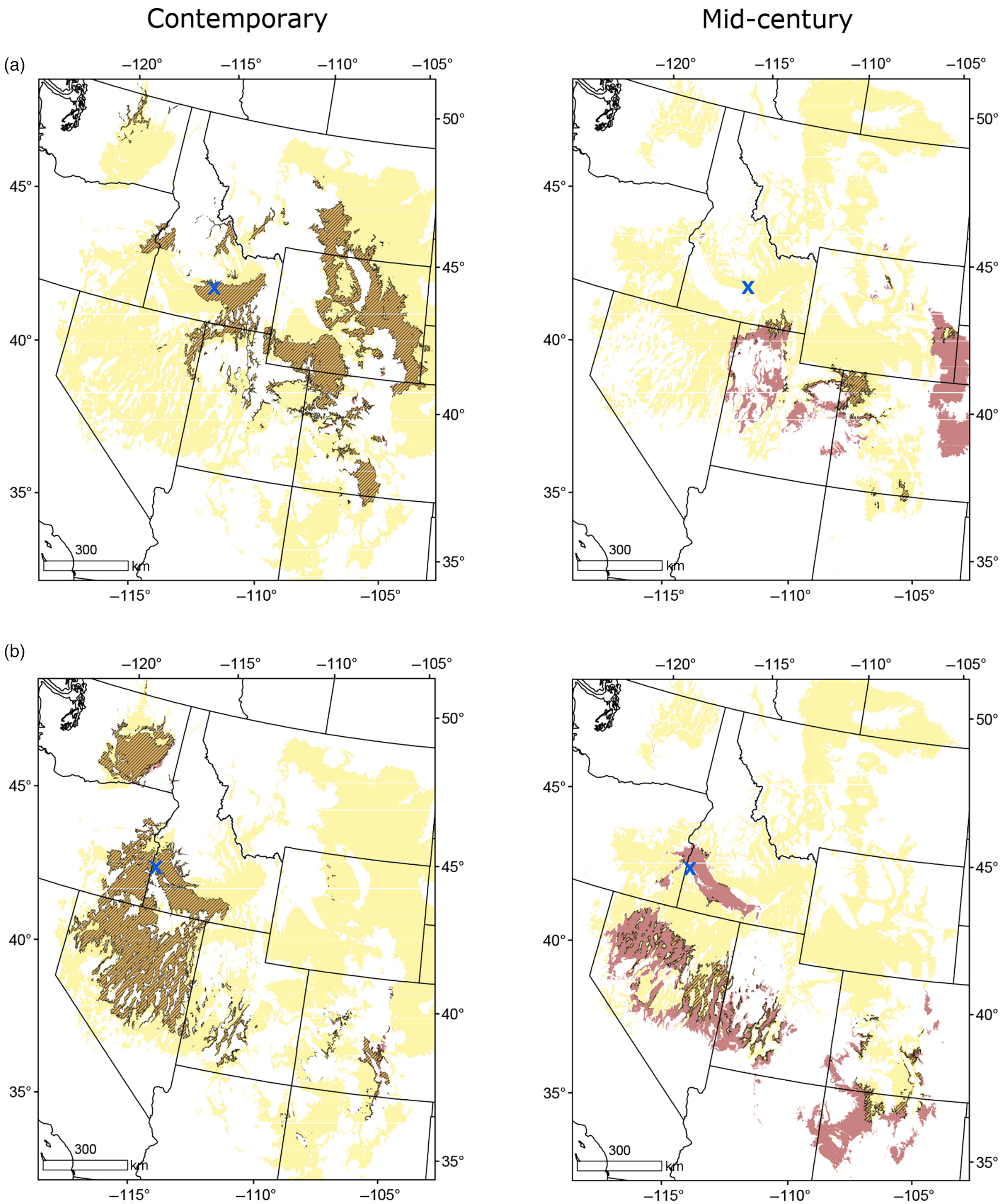

FIGURE 3 Areas of suitable seed sources created using the Climate-Smart Restoration Tool for contemporary and mid-century climates (RCP 8.5). Two wildfire sites are shown by a blue x: (a) the Preacher fire and (b) the Soda fire. The yellow polygons show the species distribution model (SDM) for the respective climate periods. Areas of suitable seed sources are shown by an orange cross-hatched pattern. The coral color in mid-century projections shows the predicted loss of suitable seed-source areas based on the contraction of the SDMs, leading to limited availability of seed. For both fires, suitable seed-source areas from which to collect are dramatically reduced by mid-century (also see Table 4).

Case study 3: Gap analysis for seed planning for future reforestation in western Oregon and Washington

To support climate-smart reforestation planning, existing seedlots need to be evaluated to determine if they are sufficient to meet reforestation needs under a changing climate. The Pacific Northwest Region of the USDA Forest Service has established Douglas-fir seed orchards to provide seed for more than 50 zones (elevation bands within geographically delineated areas) in western Oregon and Washington west of the Cascades. The initial intent of each National Forests was to provide seedlots for their local use. Given climate change, however, each National Forests will be increasingly looking south to other National Forests for adapted seedlots, particularly for their lower elevation planting sites. The question arises of whether the existing seed orchards are sufficient to meet the needs of the National Forests in the Pacific Northwest in the future.

We used the SST to identify gaps in available seedlots from seed orchards for their adaptation to a mid-century climate. To find planting sites for a particular seedlot, we mapped planting sites adapted to seedlots from each orchard block (where an orchard block was designed to produce seed for a local zone). We used the climate variables MCMT and SHM with default TLs under RCP 8.5 to map the climatic match. We then exported the maps to a GIS and produced a gridded map of the spatial overlay where each grid was assigned a value of the maximum climatic match of all the overlaid maps. Areas without a climatic match were considered to be gaps where managers might seek additional seedlots adapted to the future climate either through new stand collections or from the inventories of other land management entities. Locations of seedlots adapted to future climates in those gaps may then be found using the SST or CSRT with the objective of finding planting sites for seedlots.

The gap analysis using all orchard blocks indicated that the seedlots from the Forest Service seed orchards are suitable to meet the reforestation needs of most National Forests west of the Cascade crest considering the climate of the mid-century (Figure 4). Gaps were identified only for the lower elevations of the Rogue-Siskiyou and southern Umpqua National Forests in southwest Oregon. Indeed, seeds from the National Forest seed orchards in the Pacific Northwest Region are suitable for the mid-century climate of all of western Washington and much of western Oregon except for the warmer and drier locations in the Willamette Valley and southwest Oregon. Gaps in coverage may be filled by seed sources from northwest California as indicated using the SST to map seedlots for planting sites within the identified gaps.

An additional consideration with respect to seed planning is the risk of wildfires or disease and insects. These are factors that may be exacerbated by climate change. This gap analysis could be combined with mapped outputs of risk from those factors across the landscape to further prioritize where to collect seed either in native stands or seed orchards.

DISCUSSION AND CONCLUSIONS

The SST and CSRT are valuable management tools that allow natural resource managers to consider options for responding to potential maladaptation of plant populations due to climate change. An important feature of both tools is that they are flexible and can accommodate the needs of a wide variety of users. The tools are applicable to all of North America north of southern Mexico. They can address both questions of suitable seedlots for a planting site or suitable planting sites for a seedlot. They are applicable to any plant species given the best available knowledge of the climate variables important for adaptation of populations and acceptable climatic TLs. Thus, the tools are valuable for species with little genetic information based on assumptions of climatic adaptation. Although default climate variables of MCMT and SHM may be chosen, assumptions about climate variables and TLs may be explored by considering different variables and TLs. Genetic knowledge for some species is considerable, and the tools have incorporated knowledge from genecological studies for some species in the form of a multivariate climate using the Function approach. Presently the tool is limited to 16 climate variables of temperature and aridity. Future improvements may incorporate additional climate variables as they are identified by users and communicated to the programmers, including additional climate variables representing extremes in climate that may be important for explaining adaptive variation (although most likely correlated with mean values). Furthermore, genecological functions for additional species may be added as they become available.

An important feature of the tools is that they allow managers to scale-down to the specific locations of seed collections and restoration or reforestation sites. An alternative approach, however, is to bulk seed sources across a geographically delineated zone, or when collected from a single stand, simply identify the seed source by the zone. Foresters have relied upon fixed-boundary seed zones for both seed collection and deployment for more than a half-century in many regions of the United States and Canada, and many seed collections in seed inventories are identified only by seed zones. The SST and CSRT

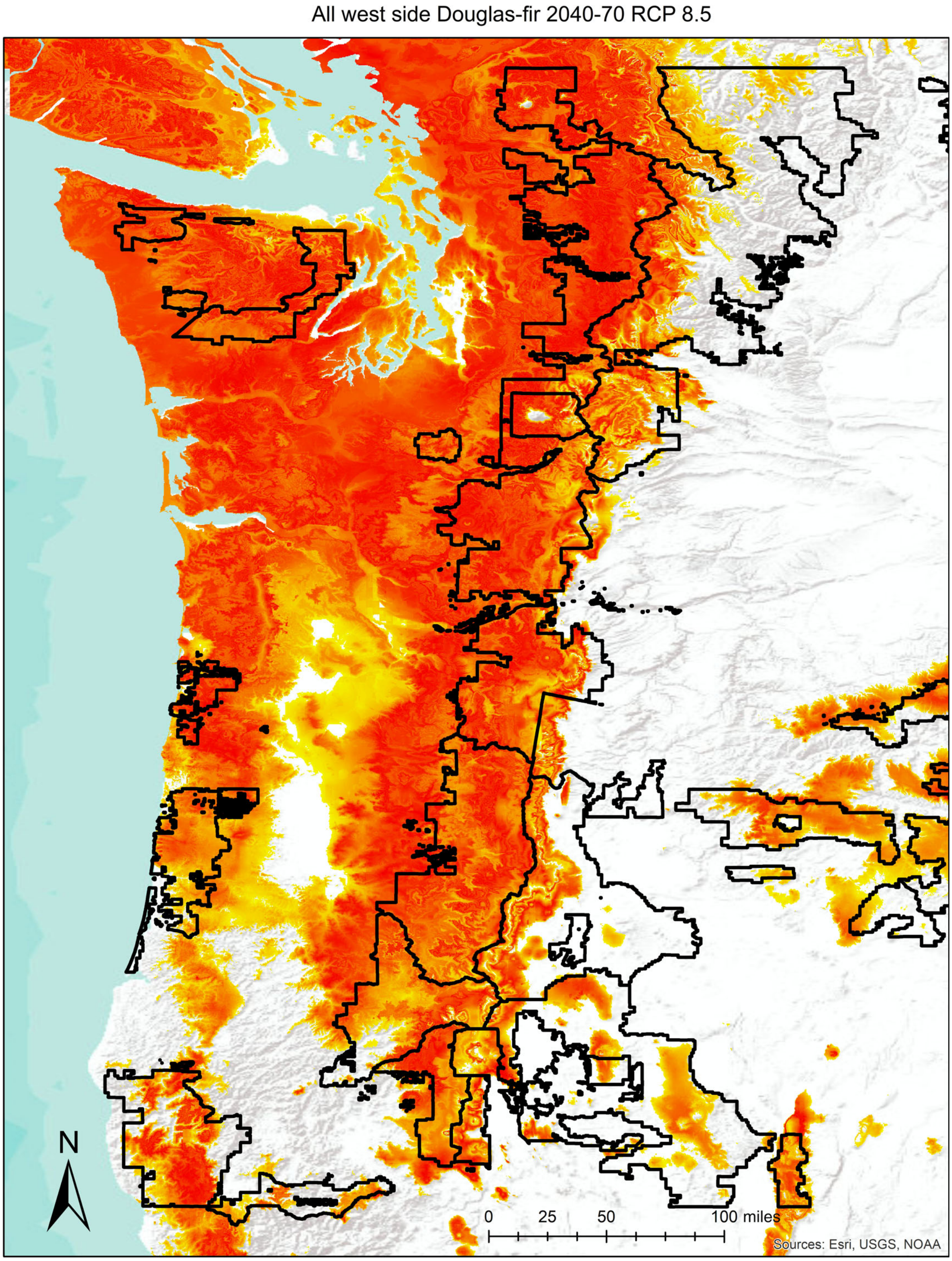

FIGURE 4 Gap analysis indicating the climatic match of seedlots from all US Forest Service seed orchards in western Oregon and Washington for a future projected mid-century climate (2041–2070 RCP 8.5). The climatic match is scaled from 100 (bright orange) to near zero (light yellow). Gaps are indicated by areas that remain uncolored. National Forest boundaries are outlined by black polygons. 1 mile = 1.609 km.

can accommodate seedlots that are identified by zone, and not by the specific location within the zone, by using the climatic center of the zone to determine the climatic match to a planting site. For the objective of finding planting sites for a seedlot, this may be done by choosing the Zone method and using the climatic center of the zone rather than the climate of the specific location. For the objective of finding seedlots for a planting site, the resulting map will show the locations of highest climatic match, at which point the user can click on the map (without setting the point) to see what seed zones overlap that location. Although zones are commonly used for seed collections, seedlots from a single stand or from collections across a relatively narrow geographic or climatic range allow for higher precision of the CTD when matching the climate of seedlots and planting sites. However, when a seed collection is from an unknown location or several locations within a climatically diverse zone, determining an accurate climatic match (as opposed to precise) may be difficult. For example, if a seed collection of an unknown location comes from a cooler area within a climatically diverse zone, assisted population movements may not be as far in the direction of warm to cool sites as expected and stands may not be as well adapted to future climates as desired. If a collection of an unknown location comes from a warmer area within a climatically diverse zone, assisted population movements from the warm to cool site may result in unexpected cold damage in the near-term. If the planting site is only identified by its zone, the inaccuracy of the climatic match becomes even greater. The problem of inaccurate CTDs may not be a problem for seedlots that include parents from locations throughout a zone. Such is the case for seedlots from seed orchards in which many parents from throughout a zone are grouped together to pollinate each other. Indeed, among-population genetic diversity may be desirable to buffer seedlots from uncertainty.

Several factors lead to uncertainty in the climatic match between a seedlot and planting site. First, populations can vary around the transfer function such that any single population may not fall exactly on the line that represents the response of a population to a specific climate. Second, in the case of long-lived species, there is uncertainty with respect to the vulnerability of different life stages to maladaptation. Seedlings are particularly vulnerable to stresses from heat, moisture deficit, and cold. Multiple, repeated stresses over the life of a stand may lead to the same vulnerabilities at later ages, as well as impacts from diseases and insects (St.Clair et al., 2020). What is certain is that populations must be adapted to the near-term climate to survive to be adapted to the long-term climate. Third, future climate projections are uncertain due to differences in assumptions and structure among general circulation models and unpredictable future emission levels driven by social choices and global political decisions. The tools are limited to a choice of six climate projections (two RCPs × three future climate normals). Although individual models may span a greater range of outcomes, a choice of six climate projections should well bracket a range of climate change projections from likely best-case to worst-case scenarios, Future improvements to the tools may include additional and updated projections, including those from the more recent IPCC AR6 (2021). Meanwhile, users may further explore uncertainty by considering more extreme models to determine the future climate at locations of planting sites and seed sources from online resources such as ClimateNA.

Although climate futures are a moving target, managers should aim for a future warmer climate that does not move a population too far from a warmer to cooler site such that the risk of cold damage is high in the near-term. The best match is the seedlot that has a high climatic match for the time period furthest into the future (a CTD equal to zero) but is still within the climatic TL for the 2011–2040 projected climate normal, or, even more conservatively, the 1981–2010 climate normal. A climatic TL of 2–3°C for winter temperatures seems sufficient to ensure cold adaptation in the near-term based on long-term provenance tests and experience with forest tree seed zones in Washington, Oregon, and California (St.Clair et al., 2020; Wang et al., 2006). Given projected rates of climate warming in the Pacific Northwest, we should be able to aim for a mid-century climate to have a high climatic match for the future and still be adapted to cold temperatures in the near-term. Regions at higher latitudes or more continental climates are experiencing faster rates of warming and managers in those regions may only be able to aim for a climate of the next couple of decades. Nevertheless, the uncertainty associated with population variation, vulnerability to maladaptation of different life stages, and climate projections can be buffered by ensuring genetic diversity of seedlots through purposeful design of population mixtures, as well as a sufficient number of parents within-populations.

Another important feature of the SST and CSRT is the ability to input a list of seedlots from a seed inventory to compare suitability to a planting site, or a list of planting sites to compare suitability to a seedlot. The resulting map and table indicating the climatic match for each seedlot or planting site in the list allows the user to prioritize seedlots or planting sites for reforestation or restoration, as well as design population mixtures that target different futures (or assumptions such as climate variables and future climate scenarios). The resulting table gives the CTDs for each individual climate variable. This allows the user to consider each climate variable separately when prioritizing seedlots or planting sites for their match, including consideration of the direction of the source movement. For example, the user may decide to prioritize seedlots for a planting site based on the best match for MCMT, while keeping the climatic difference for SHM within the acceptable TL (as in the first case study example above). As another example, the user may consider movements in the direction of maritime to continental climates as more acceptable (i.e., allowing for a larger transfer distance) for avoiding foliar diseases than movement from continental to maritime climates.

Suitable locations for seed collections or future planting sites may be constrained based on the current and future modeled range of the species. The tools do not indicate which species should be used for reforestation or restoration considering climate change. Information about current and future climatic niches of species may be found elsewhere in the literature (Hamann & Wang, 2006; Iverson et al., 2008; Rehfeldt et al., 2006) or on websites (e.g., Climate Change Tree Atlas: https://www.fs.fed.us/nrs/atlas/tree/, Species Potential Habitat Tool: https://specieshabitattool.org/spht/). A conservative approach for assisted migration would be to favor species that are currently present at a planting site or nearby (M. I. Williams & Dumroese, 2013; Winder et al., 2011). Furthermore, when faced with a choice of seedlots with similar climatic matches, a conservative approach would be to favor the seedlot that is geographically closer.

The goal of restoration or reforestation activities is to determine the best fit, or climatic match, to future climates, while avoiding failures from maladaptation to near-term climates and maintaining genetic diversity to account for uncertainty. Down-scaled climate projections are now widely available (Rehfeldt, 2006; Wang et al., 2016), and determining the climatic match between the past climate to which seedlots are adapted and future climates in which plants are expected to be adapted may be easily calculated by simply using a spreadsheet. The primary advantage of the SST and CSRT, however, is that the mapped output allows users to visualize the climatic and adaptive differences over space and time. Alexander von Humbolt recognized the value of maps in understanding the natural world when he wrote: "Anything that has to do with extent or quantity can be represented geometrically. Statistical projections [charts and graphs], which speak to the senses without tiring the intellect have the advantage of bringing attention to a large number of important facts." (from Alexander von Humboldt, Atlás géographique et physique du Royaume de la Nouvelle-Espagne, lxxxiii-lxxiv, quoted in Anne Godlewska, Geography Unbound: French Geographic Science from Cassini to Humboldt. Chicago: University of Chicago Press 1999, p. 257).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The project source code and data are available under the open-source BSD 3-clause license. The source code (Molnar et al., 2022a, 2022b; Molnar & Klinkow, 2022) is available from Zenodo: https://doi.org/10.5281/zenodo.6326292, https://doi.org/10.5281/zenodo.6326296, and https://doi.org/10.5281/zenodo.6326300. The data used in the tool (Stevenson-Molnar, 2022) are available from Zenodo: https://doi.org/10.5281/zenodo.6354816. The data were prepared and processed using scripts (Molnar, 2022) available from Zenodo: https://doi.org/10.5281/zenodo.6345538.

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