Climate Smart Restoration Tool User Guide

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Introduction

History of the Seedlot Selection Tool (SST) and the Climate Smart Restoration Tool (CSRT)

The SST and CSRT were originally designed to have parallel methods to address seed transfer guidance for trees and non-trees, respectively. These web-based platforms included two approaches: generalized and genecological methods. Briefly, the generalized method uses climate variables to define seed transfer limits, and the genecological method uses existing species-specific trait data described by climate-based regression functions to define seed transfer limits. For more information on the SST methods see St.Clair et al. (2022). Given the substantial differences in the approaches described below, the genecological data within the CSRT has been transferred to the SST and the URL for the CSRT (https://climaterestorationtool.org/) houses the new generalized approach described below.

New CSRT and SST comparison

The SST generalized "custom" method and the new CSRT (henceforth CSRT) use Euclidean distance derived from climate variables, hereafter referred to as climate distance, to calculate generalized seed transfer thresholds and identify climate analogs. The SST can be thought of as a sandbox approach where the user can choose from 1 to 6 climate variables and set each climate variable threshold independently. The generalized approach of the CSRT (Richardson et al. 2024) uses 20 climate variables (Table 1) to define climate analogs. Instead of user-specified thresholds for each climate variable, the CSRT uses a Euclidean climate distance value from the 20 standardized variables to categorize seed transfer thresholds as strong, moderate, and weak. Climate distances are strongly correlated to elevation (Richardson et al. 2024). Existing knowledge from common garden studies has shown plant adaptations follow altitudinal clines, and adaptive trait differences are generally reported in species with elevation differences between 300m and 500m (e.g., Rehfeldt 1994, St.Clair et al. 2005, Sáenz-Romero et al 2012, Joyce and Rehfeldt 2017, Ortiz-Bibian et al 2017, Leites and Benito-Garzón 2023). Therefore, elevation is used to gauge thresholds. We set climate distance values so that a 300m elevation difference between two points defines a weak threshold among the vast majority (> 98%) of randomly sampled point pairs (see Richardson et al. 2024, Table S4 and https://github.com/ermilano-fs/ClimDist/).

Another difference in the CSRT is the use of vegetation inventory and biome data (Table 2) to provide ecological and species information. The CSRT maps plot data within the seed transfer limit, provides tables of plant species, and compiles reports of species frequency among plots within a climate distance threshold. More details are provided below.

The goals of the CSRT are to:

- provide guidance for seed transfer by identifying areas with analogous climate for current and midcentury time periods
- assess potential species for ecosystem restoration using compiled species data from vegetation inventory plots
- infer vegetation transitions over time using current and midcentury climate to predict changes in species frequencies

Tool Operation

Entering a location: First, within the “Settings” sidebar, enter the desired geographic coordinates under the “Location” subheading or click on the map. Keep in mind that clicking on the map is less accurate, especially when the map is viewed at higher spatial scales. Once the coordinates have been entered, a green placemark will indicate the reference point. Elevation will be listed below the coordinates based on a 30 m digital elevation model.

Determining the reference period: Next, under the “Reference Time Period” choose between two climate reference periods: historical (1961–1990) and current (1991–2020). The reference time periods are based on 30-year normals of the 20 variables used to calculate climate distance (Table 1). We recommend a historical reference if the interest is in long-lived species that have experienced historical climates and a current reference for short-lived species that have experienced a contemporary climate.

Running the tool: Last, click the “Run” button to view biome and vegetation plot data within the climate distance thresholds. In the map viewing area, symbols show the location of vegetation and/or biome plots within the climate distance. These matches can be considered climate analogs to the selected reference site. Symbol shape indicates time period: triangles represent the reference time period and circles represent mid-century time period. Symbol colors represent strong, moderate and weak thresholds, which are three levels of climate similarity with strong being most similar to the selected location. This legend can be found under the “Results” heading. The threshold matches and time period can be toggled on or off depending on the user’s needs (see Example 3). Below the threshold matches, the “Threshold Area” subheading, described in Data Sources, can be toggled on or off to show a contiguous area under the weak climate distance threshold for the mid-century and/or reference time periods. Each threshold area can be downloaded as a GeoTIFF, GeoJSON, or WKT for compatibility with GIS software. The “Download map” button provides another option to download the full map as a pdf.

Viewing the data tables: Below the “Run” button is the “View data table” button. This populates data tables based on the reference point and currently specified thresholds. Three data tables can be viewed and downloaded from the data table window using the tabs in the header. “Raw Data” includes a list of spatial and species information for all biome and vegetation plot points within the specified climate distance threshold. “Biomes” and “Species” compile the raw data into summary tables. “Biomes” provides a count of biome types for reference climate and mid-century climate analogs. “Species” calculates a species frequency (i.e., the number of vegetation plots with a species presence / number of total vegetation plots) for reference and mid-century climates. Note that species frequency requires a minimum of 30 vegetation plots for the calculation. A warning message will appear above the column headers when this criterion is not met. Users can adjust the thresholds (strong, moderate, and weak) using the “Thresholds” drop-down button. The columns can be sorted alphabetically or numerically by clicking on the column headers. Each table can be downloaded using the green button in the lower right of the data window.

Data Sources

Climate data: Climate variables are sourced from ClimateNA v7.50, which provides downscaled PRISM (Daly et al. 2008) gridded monthly climate normal data to scale-free point locations (Wang et al. 2016). More detailed information on the climate data and its geographic extent can be found here. Mid-century climate projections for 2041-2070 30-year normals are an average of 3 Shared Socioeconomic Pathways (SSPs) scenarios from ensembles of 8 General Circulation Models (GCMs) of the Coupled Model Intercomparison Project (Mahony et al. 2022). GCMs include: ACCESS-ESM1-5, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, GISS-E2-1-G, MIROC6, MPI-ESM1-2-HR, and MRI-ESM2-0. SSPs include: SSP245, SSP370, and SSP585. Climate variables are annual, monthly, and seasonal temperature and precipitation measures as well as derived interaction terms (Table 1). For the "Threshold Area" layers, the data source is GeoTIFF files that were created for this tool, one for each of the 20 climate variables, and for each time period. These were created using ClimateNA and a 30 arc-second

DEM of North America. The threshold areas are delineated by Euclidean climate distance values (as described above) with a limit of the weakest threshold.

Species inventory plot data: Vegetation inventory plot data (Table 2) comes from several national program sources. Canadian inventory data were obtained from the Canada National Forest Inventory (NFI) and Canadian National Vegetation Classification (CNVC) programs (National Forest Inventory 2024, Baldwin et al. 2019). Mexico inventory plot data comes from the National Forest Commission (CONAFOR) National Forest and Soils Inventory (INFyS). Species presence indicates an occurrence during one or more inventory cycles between 2004-2020, data for each cycle is publicly available. US inventory plot data comes from two sources, the USDA Forest Service's Forest Inventory and Analysis (FIA) program and the USDOI Bureau of Land Management's Assessment, Inventory and Monitoring (AIM) Strategy. Both datasets are publicly available. FIA plots cover the US in a systematic grid and can be found on public and private land. Due to privacy laws, Canadian and US plot coordinates are "fuzzed" to mask the precise geographic location; however, the degree of geographic imprecision is smaller than the resolution of climate data (~1 km^2) used in this tool. AIM plots use random sampling to provide a spatially balanced representation of land conditions across the Western US. However, there may be inconsistencies in plot distribution due to only being available on public lands. This should be noted when interpreting species frequency results.

USDA PLANTS database: Vegetation inventories use species codes that can be found in the USDA PLANTS database. Species name, growth habit, native status, and a species page link are provided in the species tab of the results table. *Note: Species found only in Mexico do not have database links, but the scientific name and growth type are provided.*

Biome data: The biome dataset is not comprised of on-the-ground inventory plots but rather provides a backbone of reference points distributed across the continent with an associated biome classification based on Brown et al. (1998). These biomes were classified based on climate by Rehfeldt et al. (2012) and more recently by Campbell & Wang (2025). This dataset is included to fill in gaps where there is little or no coverage of inventory plot data (see below: Vegetation Plot Coverage). Points were sampled from 1.75 million observations in 64 biotic communities classified by Brown et al. (1998). These biomes were updated and reclassified based on climate in Campbell & Wang 2025.

Map layers: Users have the option of choosing several map layers that can aid in interpretation. At the bottom right of the map interface, above the map magnification icons, there are options to view either topographical or satellite imagery maps. At the top left, the “Map layers” button provides options to view the map with US counties, Omeriks level III ecoregions, or biomes. The biomes, which are the ecological classification used in the biome data, have options to view current, mid-century, or late-century projections (see Campbell & Wang 2025). Biome names appear when the cursor is hovered over a colored pixel.

Results and interpretation

Vegetation plot coverage: It is important to note that some regions of North America have limited vegetation plot data or that the plot data is focused specifically on woody species. Below are regions that have limited vegetation plot coverage and rely heavily on biome points:

- Canada: Vegetation data from non-forested biomes (e.g., northern tundra and prairie grasslands), and biomes with low tree cover (e.g., Subarctic Forest Tundra/Woodlands), is very limited.
- Mexico: Data is limited to woody species.
- AIM plots: This plot data is a random sample limited to DOI lands in Western states. Target points that rely heavily on AIM analogs should be interpreted with caution since they may not be entirely representative of all plant communities within the seed transfer limit.
- FIA plots: Eastern USA FIA plots consist of woody vegetation. However, western FIA plots consist of both woody and non-woody vegetation.
- More specifics can be found in Table 1.

Predicted vegetation change: The predicted change column can be found in the species summary table. Species frequencies are calculated for the reference and mid-century climate using the formula below:

$$Species\ frequency = \frac{\Sigma\ Plots\ of\ species\ i\ presence}{\Sigma\ plots}$$

Change in frequency between the reference time period and mid-century is determined using a Fisher’s exact test with $p < 0.05$ significance. Each species is assigned to a predicted change category: increase, decrease, or stable. Stable indicates that the species frequency does not significantly change from the reference period to mid-century. Increase or decline indicates a significant difference in species frequency between reference and mid-century. Users should interpret these results as potential trajectories of vegetation change based on consensus projections of future climate. Other ecological conditions, such as micro-topographic factors (< 1km), can have modifying effects and therefore local expertise may be needed to refine decisions about appropriate species.

Novel climates: Climate analogs, biome and vegetation plots within the climate distance thresholds, vary among sites and between the reference and mid-century climate. Sites with few or no mid-century analogs suggest that the emerging climate will be novel compared to current or historic conditions. Sites with novel climates suggest that there is greater uncertainty in the plant species capable of occupying such conditions. In general, selecting “Current” as the Reference Time Period will reduce climate distances to mid-century and increase the likelihood of identifying mid-century analogs (see Example 2). In our observations, geographic and topographic positions play a role in analog abundance. Areas with limited analogs typically appear in basins or near the coast. Further study is needed to determine whether these observations have statistical merit.

Species code errors: Infrequently, species names are incorrect. This is typically caused by an error in the species code listed in the plot data records. Another source of error may come from renaming of genera, species, or separate listings for the same species with different subspecies or varieties. An example is *Artemisia tridentata*, big sagebrush. Some data sources are species level sources, while other data sources list out subspecies (e.g. *A. tridentata* ssp. *vaseyana* and *A. tridentata* ssp. *wyomingensis*. Users should be cognizant of potential multiple listings for their species of interest.

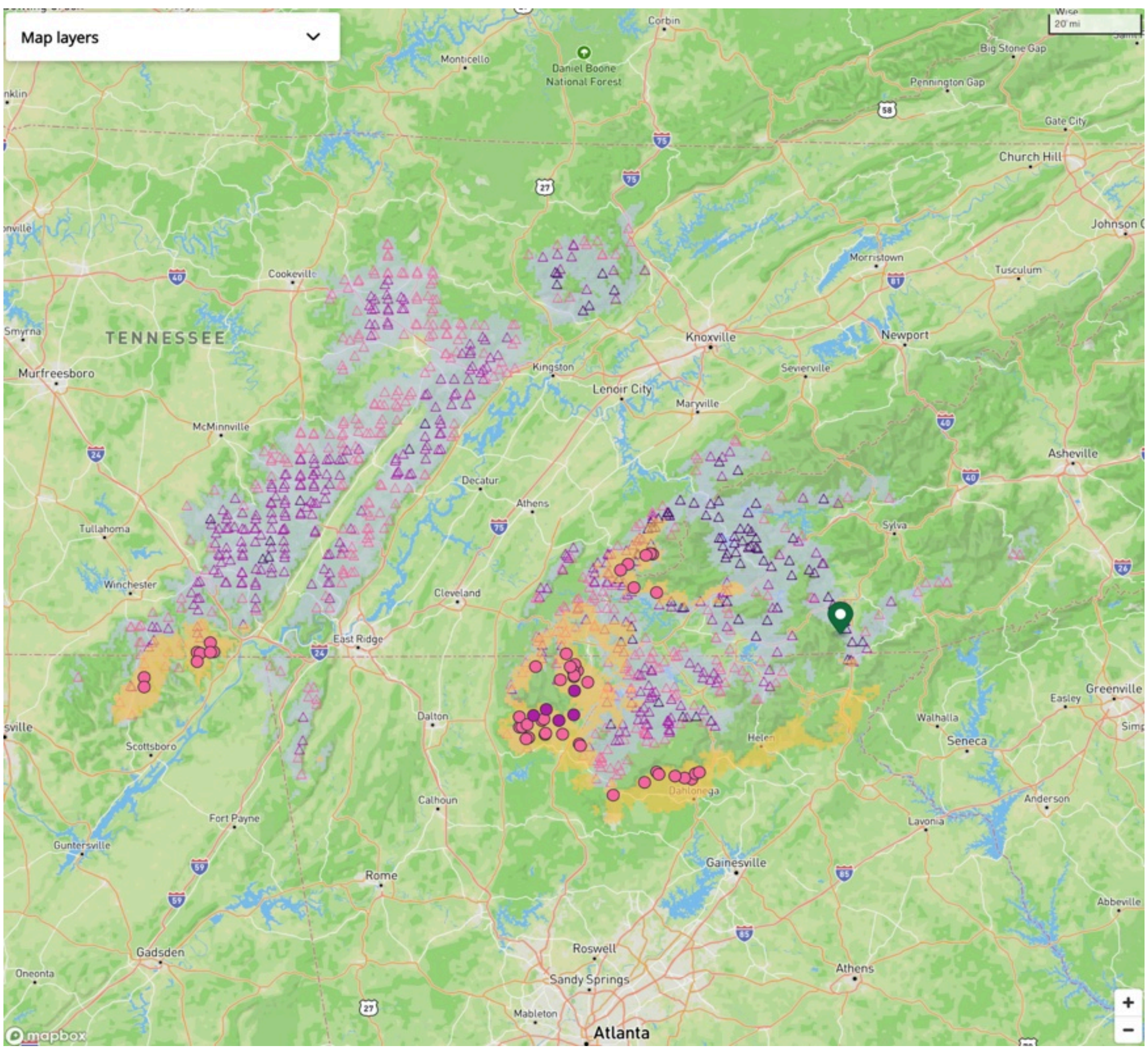
Genus-level identification: For a small fraction of plants, identities are limited to genus level (i.e., the specific epithet is missing). This usually indicates the collector was not confident in making a species determination, therefore these results should be interpreted with caution.

Examples

Below, three examples are provided to aid in interpretation of the results. These examples are designed to show a variety of analog projections.

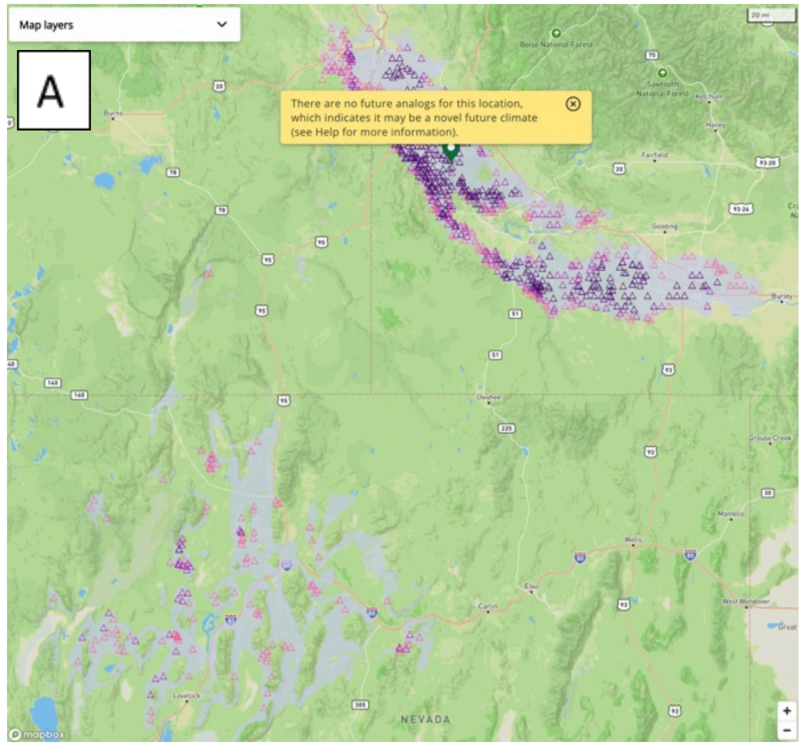
1. Coweeta Experimental Forest (35.05815, -83.43195), current (1991–2020) reference time period.

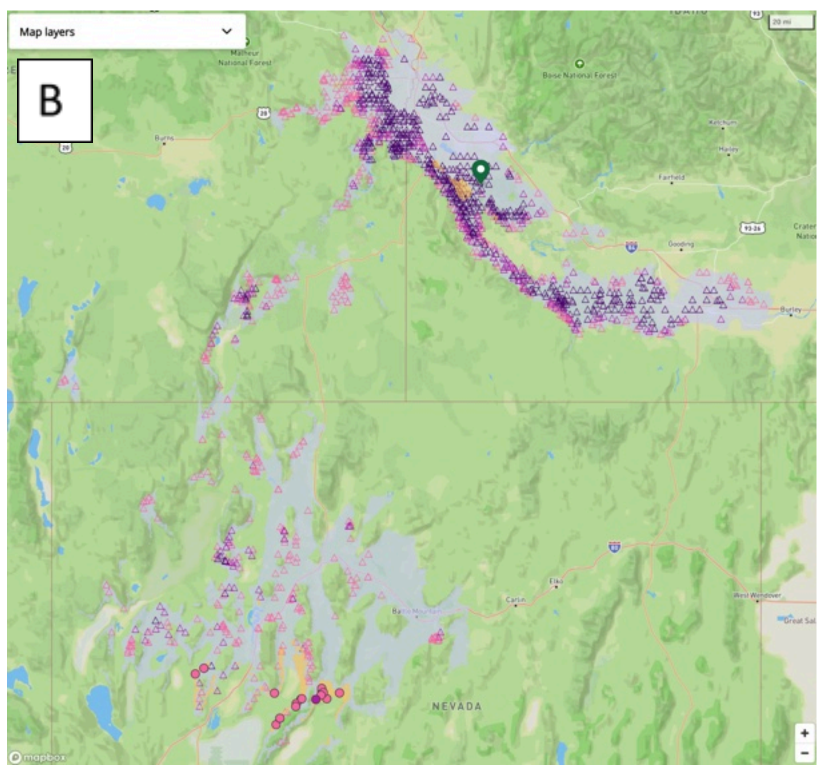
Coweeta Experimental Forest, green pin, has a moderate amount of current (triangles) and limited future analogs (circles). Based on strong, moderate and weak thresholds, major tree species (e.g., red maple, white oak, and tulip tree) remain stable between current and mid-century. Here, reforestation guidance would be to maintain desired current forest species and source seed for reforestation from lower elevations in northern Georgia and southeastern Tennessee (i.e., orange polygons).



2. Birds of Prey (BOP) Conservation Area (43.34737, -116.39526), historical (1961–1990) and current (1991–2020) reference time period.

The Birds of Prey site is an example to contrast historical and current reference conditions. Under a historic reference period, mid-century analogs, circles, are absent and historic analogs, triangles, are abundant (A). Similarly, current reference period analogs are abundant and largely overlap with the historic reference. However, under a current reference, mid-century analogs appear in Nevada (B). These differences can be explained by the change in climate distance between historic and current reference conditions, equivalent to about 0.5°C warming. Therefore, current reference conditions have smaller climate distances to mid-century than historic, resulting in the appearance of mid-century analogs. Restoration guidance for the BOP would be to restore stable species (e.g., Sandberg Bluegrass and Wyoming big sagebrush), but given the limited future analogs and the abundance of invasive species (e.g., cheatgrass), there is predicted higher risk for restoration failure.





3. Boundary Waters (47.94568, -91.69678), historical (1961–1990) reference time period.

Boundary Waters represent a site located in the transition between boreal to northern temperate forests. Here, boreal species (e.g., paper birch and black spruce) decline, while temperate species (e.g., green ash and northern red oak) are predicted to increase. The seed transfer limits for this site follow a latitudinal pattern, typical for areas with low topographical relief. Seed transfer guidance would be to move seed sources about 300 km from the south. The polygon layer shows the weak threshold area for historic, light blue, and mid-century, orange (A). Given the abundance of analogs for this reference site, it might be desirable to limit seed transfer to the strong threshold. Weak and moderate analogs have been toggled off (B).

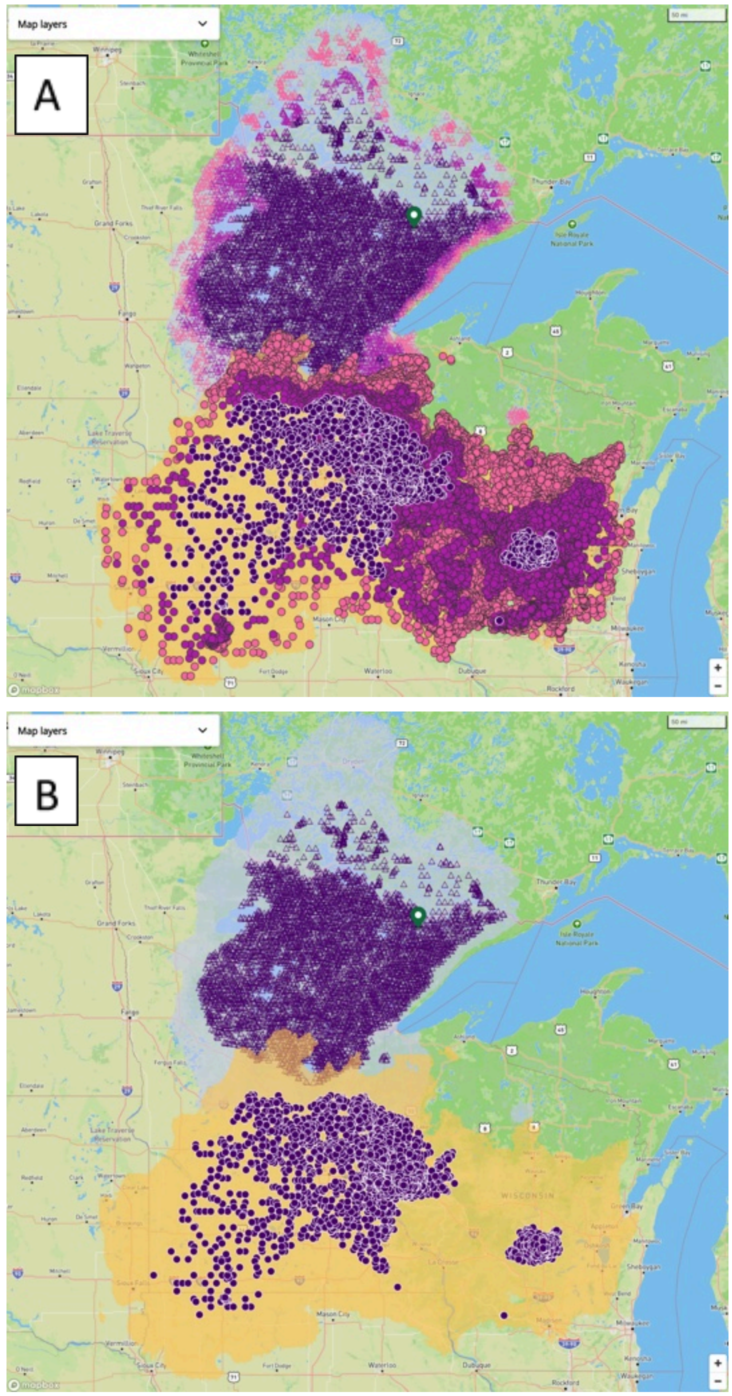


Table 1. Climate variables used to calculate climate distance in the CSRT.

Acronym	Climate Variable	Units
MAT	mean annual temperature	°C
DD5	degree-days above 5°C	days
bFFP	the day on which the frost-free period begins	Julian calendar day
MCMT	mean coldest month temperature	°C
Tmax_sm	summer mean maximum temperature (June to August)	°C
Tdiff	Summer-winter temperature differential, mean temperature in the warmest month - MCMT	°C
MAP	mean annual precipitation	mm
PPT_wt	winter precipitation (December to February)	mm
ppt_sp	Spring precipitation (April to May)	mm
ppt_sm	Summer precipitation (July to August)	mm
GSP	Growing season precipitation (April to September)	mm
Pratio	precipitation ratio, GSP / MAP	na
ADI	annual dryness index, sqrt(DD5) / MAP	na
SDI	summer dryness index, sqrt(GSDD5) / GSP, where GSDD5 is growing degree days > 5°C between March and August	na
ADIminDD0	ADI x (1 + degree-days < 0 °C), with negative degree days based on the minimum temperature	na
SDIminDD0	SDI x (1 + degree-days < 0 °C), with negative degree days based on the minimum temperature	na
MAPDD5	(MAP * DD5) / 1000	na
GSPDD5	(GSP * DD5) / 1000	na
SMratio	summer precipitation ratio, ppt_sm / GSP	na
RSDS	surface downwelling shortwave radiation	MJ m^{-2} d^{-1}

Table 2. List of databases and their attributes.

Database	Basic unit	Species identification	Number of Records (K)	Compiler
North America biomes	Shape file polygons	none	436.5	Campbell & Wang 2025
US National Forest Inventory (FIA)	ground plots	FIA east: trees and smaller woody species FIA west: trees, shrubs, forbs, grasses	212.5	FIA DataMart
Canada's National Inventory (NFI)	ground plots	Trees and smaller woody species	34.8	NFI (2024a, 2024b)
Canadian National Forest Inventory (CNVC)	ground plots	Trees, shrubs, forbs, grasses, non-vascular plants	51.5	Baldwin et al. (2019)
Mexico National Forest Inventory (INFyS)	ground plots	Trees and woody species	22.0	CONAFOR INFyS
US BLM Geospatial (AIM)	ground plots	Shrubs, forbs, grasses, noxious weeds	39.7	BLM AIM

How to cite

Methods:

Richardson, B. A., Rehfeldt, G. E., Sáenz-Romero, C., & Milano, E. R. (2024). A climate analog approach to evaluate seed transfer and vegetation transitions. *Frontiers in Forests and Global Change*, *7*, 1325264. https://doi.org/10.3389/ffgc.2024.1325264

Tool and output:

Richardson, B. A., Milano, E. R., White, L., Ishkarin, K., Stevenson-Molnar, N., Joseph, G., Campbell, E.M., Saenz-Romero, C. (2025). Climate Smart Restoration Tool. https://climaterestorationtool.org

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Glossary

Climate analog: geographic locations that share high climate similarity

Climate distance: a Euclidean distance, a straight-line distance between two points in climate space

Seed transfer threshold: the highest climate distance value recommended for transfer of seed between locations. Thresholds (strong, moderate, and weak) are intended to accommodate the variation observed in adaptive genetic breadth among plants.

Shared Socio-economic pathways (SSPs): potential demographic and economic outcomes that affect greenhouse gas emissions. Follow the link for more information.