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Student Research Report

Climate adaptation scenarios for a resilient future at UBC Botanical Garden:

Modeling Species Distribution for Acers griseum, pentaphyllum, circinatum, and macrophyllum

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Prepared for: SEEDS and UBC Botanical Garden

Course Code: FCOR 599

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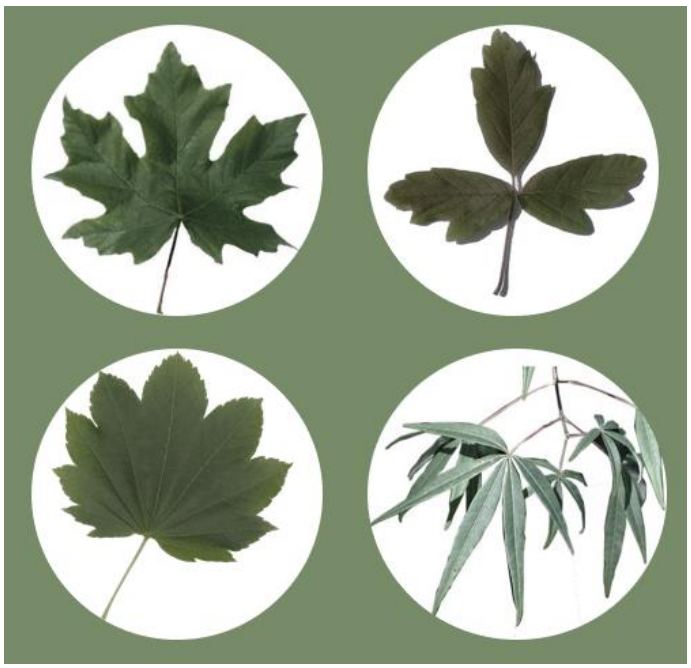

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Abstract

As anthropogenic climate change continues to disrupt forests and species' ecological niches, there is increasing urgency to create plans surrounding adaptation and mitigation for especially vulnerable species. The University of British Columbia's Botanical Garden (UBCBG) wants to understand species responses to climate change and whether species within their collection will be able to survive in the Garden, given the effects of climate change. One especially important collection UBCBG curates is maple (*Acer*) trees, currently leading the global consortium of *Acer* and housing over 50 different species. This study examined the survival probability of four *Acer* species UBCBG curates including: five-fingered Maple (*Acer pentaphyllum* Diels), considered critically endangered; paperbark/bloodbark Maple (*Acer griseum* (Franch.) Pax), considered endangered; bigleaf maple (*Acer macrophyllum* Pursh), not endangered; and vine maple (*Acer circinatum* Pursh), not endangered. Maxent, a popular machine-learning algorithm, was used with open-source WorldClim's 19 bioclimatic variables and provided presence-only occurrence data to conduct species distribution models for each tree species. Each model was evaluated using area under the curve (AUC). AUC scores were considered 'good' for each model; *A. griseum* - 0.95; *A. pentaphyllum* - 0.877; *A. macrophyllum* - 0.986; *A. circinatum* - 0.976. However, future distribution maps contain questionable results due to insufficient field data to inform the model, such as in-field temperature, moisture, elevation, and surrounding vegetation data. Though results can be interpreted as binary regarding whether or not UBCBG will be suitable for each species, they should be taken as preliminary ideas where management plans for mitigation and adaptation can be developed. This study concludes by detailing the importance of field data collection and provides future directions for research that UBCBG may consider when conducting similar analysis.

Keywords: Species distribution model, Maxent algorithm, *Acer pentaphyllum, Acer griseum,* botanical garden, climate adaptation

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Acknowledgment

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1. Introduction

Anthropogenic climate change has, and will continue, to disturb forest stands globally by increasing harsh weather events and providing optimal conditions for pests and pathogens to thrive under (Seidl et al., 2017). This has an impact on the biodiversity of tree species (Thom & Seidl, 2016), the ecological necessity for countless other species (Weber & Flannigan, 1997), and services and provisions they offer us financially (Trumbore et al., 2015). There is urgency in understanding the implications of these changes, and a need for integrating this knowledge into conservation practices. The University of British Columbia Botanical Garden (UBCBG) is one such institution that is dedicated to this level of conservation measures and has an ambitious goal of realizing climate change impacts over their most endangered species. This report examines 4 species of *Acer* (maple trees): *Acer pentaphyllum* Diels, *Acer griseum* (Franch.) Pax, *Acer circinatum* Pursh, and *Acer macrophyllum* Pursh.

Presently, *Acer* species exist in a multitude of climates across the world. New phenological studies have shown that maple trees migrated to North America from Eastern-Asia during particularly warm conditions during the Eocene (Areces-Berazain et al., 2021). Fossilized records show 91 species once occupied 28 sections in North America, though only 5 species from 5 sections remain extant today (Grossman, 2021; Wolfe & Tanai, 1987). It is hypothesized that North American *Acer* diversity was culled during glacial cycles (Areces-Berazain et al., 2021) as niche ecological models reveal many trees in that genus struggle to colonize areas with annual mean temperature at 0°C (Grossman, 2021). Grossman's (2021) ecological niche models also revealed very few shared niches across maple taxa, despite being closely related in phenology and biogeoclimatic zones. This finding is of particular interest as it indicates that predictive modeling for future scenarios relies on analyzing each maple species independent of one another, and that one cannot extrapolate assumptions for an entire genus from the results of a single species.

In 2020, The Red List of Acer identified 36 Acer species as threatened (Critically Endangered, Endangered, and Vulnerable), primarily due to urban development (Barstow et al., 2020). Concerns surrounding climate change impact on *Acer*s have largely focused on *Acer saccharum* (sugar maple) due to its economic value and ecologic ease of data acquisition (some examples include (Bishop et al., 2015; Matthews & Iverson, 2017; Murphy et al., 2009). *A. saccharum* is largely susceptible to changes of abiotic features, such as earlier thaw and dry summers, which affect quantities of harvestable syrup (Murphy et al., 2009). As the global average temperature is predicted to reach up to 4.8°C by 2081-2100 under certain carbon-concentration scenarios (IPCC, 2021), Acer may find itself capable of reaching new latitudes so long as precipitation remains regular (Jain et al., 2021; Murphy et al., 2009). However, the rigorous scrutiny applied to *A. saccharum* must be applied to other tree species in order to determine the suitability of UBCBG for these endangered species so ex-situ conservation measures may be taken.

In situ and Ex situ importance for biodiversity

In situ conservation is defined as the conservation of ecosystems, natural habitats, and preservation of species that exist *within* their natural range and surroundings (Schwartz et al., 2017). *Ex situ* differs in that conservation happens in locations where these ecosystems are *not* naturally found, but have similar enough ecoregional variables that they are comfortable existing in that climate. *In situ* collections are preferred for their wider genetic diversity (Wei & Jiang, 2021) and comparatively unrestricted range, though these are frequently endangered due to habitat fragmentation, degradation, and general disturbance (González et al., 2020). This places a high importance on *ex situ* collections which can offer horticultural expertise, human-mediated temperature and precipitation control using remote sensing, pest control and management, seed banking, and ultimately conservation. Though ex-situ collections may result in many specimens with little genetic variation or inbreeding, conservation consortiums have proven invaluable in successfully reintroducing species to their respective, native regions (Abeli et al., 2020). UBCBG is the lead institution of the Global Conservation Consortium of Acer since 2020 and UBCBG currently houses approximately 70 Acer taxa (*Maples*, n.d.), of which two are considered endangered.

Objective

This study will determine the climatic suitability of UBCBG for two North American *Acer* species listed as 'least concern': *A. circinatum*, and *A. macrophyllum*; as well as two Asian species listed as critically endangered and endangered in the The Red List: *A. pentaphyllum* and *A. griseum.* I hypothesize that the extent of suitable *Acer* habitat will shift northward and broaden, given the previous findings of Liang 2021 and Jain et al., 2021, but that this shift largely depends on future projections of precipitation. This study will not only examine four species of maple trees, but will examine future implications under two different climate scenarios (SSPs 2-4.5 and 3-7.0) in compliance with the latest International Panel on Climate Change (IPCC) report. The results will contain these scenarios projected to both 2050 and 2090 in order to visualize immediate action and long-term action, such that UBCBG may build a robust plan for future climate change resilience.

2. Study Site and Data Description

Study Site

The University of British Columbia Botanical Garden is located at 49.2478293° N 123.246107° W on xʷməθkʷəy̓əm (Musqueam) territory within the University of British Columbia, Vancouver, British Columbia (Canada). The Garden has the capability of containing plants that exist in USDA Hardiness Zones 7-9 (Mosquin, 2003) and exists in the Lower Mainland Ecoregion, which can experience warm drought-like temperatures during the summer and cold air from the Arctic over winter (Demarchi, 2011). In this ecoregion, elevation dictates appropriate zones for vegetation, as the mountainous regions to the North and East steer air currents over this ecoregion. The 'normal' (defined by 1960-1990) average annual temperature for this area is 6.7°C, and average annual precipitation is 1664 mm (as derived from WorldClim).

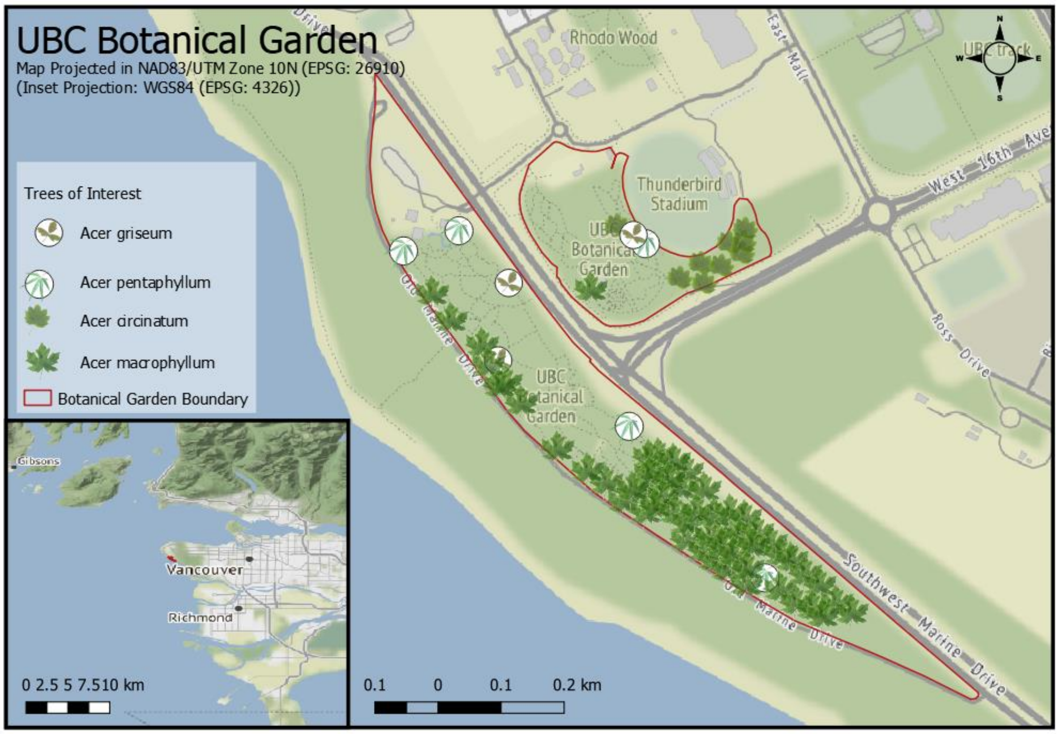

Figure 1 - UBC Botanical Garden study site with Acer trees of interest highlighted. Species include *A. griseum, A. pentaphyllum, A. circinatum, A. macrophyllum.* The red border delineates the limits of UBCBG. Inset map shows UBCBG is located in Western Vancouver. Map projected in NAD83/UTM Zone 10N.

Data Description

Tree Data

In-situ and ex-situ data points for the two threatened species (*A. pentaphyllum* and *A. griseum*) were provided by the UBCBG. In-situ locations were obtained from the IUCN Red List and ex-situ locations were obtained as part of a survey conducted in 2019 by Botanic Gardens Conservation International (BGCI) (Crowley et al., unpublished). Files contained ex-situ accessions for the species of interest and the latitude/longitude coordinates of georeferenced wild-collected accessions. Occurrence data for *A. macrophyllum* and *A. circinatum* were downloaded from the Global Biodiversity Information Facility (GBIF at https://www.gbif.org/).

Figure 2 - Map of the provided occurrence data of A. pentaphyllum and A. griseum within China. Map projected in WGS84.

<u>Climate Data</u>

Global present climate data for 19 bioclimatic variables were downloaded from WorldClim (https://www.worldclim.org/data/worldclim21.html) at a resolution of 2.5 minutes (~5 km2 at the equator). ‘Present’ or ‘normal’ climate data is defined as data collected and averaged between 1970 and 2000. ‘Present’ Worldclim data were collected from 9000 - 60 000 weather stations and interpolated using thin-plate splines with covariates that acknowledge elevation, distance to coastlines, MODIS-derived maximum and minimum of land surface temperature, and MODIS-derived cloud cover (Fick & Hijmans, 2017).

Future climate data were downloaded at 2.5 minutes using the MIROC-ES2L global circulation model. This model was selected for its consideration of processes related to plant growth and land carbon sinks (Hajima et al., 2020). These 19 bioclimatic variables for years 2050 and 2090 were downloaded from Worldclim at https://www.worldclim.org/data/cmip6/cmip6_clim2.5m.html. The chosen greenhouse gas emission scenarios’ include SSP2-4.5 and SSP3-7.0 which can be plainly defined as ‘Middle of the road’ (some countries make progress towards green technology whilst others severely fall short) and ‘Rocky Road’ (countries become hostile towards one another and make mitigation and adaptation policies extremely challenging to adopt), respectively (O’Neill et al., 2017).

3. Methods

Summary

Asian tree species data were cleaned for duplicate points. North American species data from GBIF were cleaned of any 'not available' latitude/longitude values and filtered out occurrences GBIF marked as 'preserved specimen'. Maxent, a popular machine learning algorithm (Phillips et al., 2006), was used to determine current and future distributions of all species. Asian tree species used a 'bootstrap method' of eliminating one observation from the dataset and training the model with the remaining observations, then evaluating how well the model performed by the remaining observation. For North American tree species, the model used 90% of the data for training and the model was evaluated with the remaining 10% of occurrence data, replicated 30 times over. Area Under the Curve (AUC) was taken from each evaluation and averaged to get the final AUC of the model. Bioclimatic variables that contributed less than 5% to the final model on average were removed.

Data Processing

Tree data provided by UBCBG (*A. griseum* and *A. pentaphyllum*) were cleaned for duplicates and reduced to latitude and longitude information. Observations for *A. griseum* were reduced to 66 from 71 rows, and *A. pentaphyllum* was reduced to 29 from 47 rows. *A. macrophyllum* and *A. circinatum* data were cleaned for NA values, duplicate values, and filtered for data entries that were not 'PRESERVED_SPECIMEN', as those marked as such represent herbarium specimens and archival records. This resulted in 10879 observations for *A. macrophyllum* and 4550 observations for *A. circinatum.* Both of these species had GBIF occurrence records elsewhere in the world that do not coincide with either species' geographic ranges, so these data were excluded and limited to a longitudinal extent of North America (130°W and 90°W).

Present climate data and elevation data were downloaded from Worldclim and combined by stacking and resampling. Future climate data were downloaded as TIFF files and were rasterized using the terra::rast function (Hijmans, 2021) in R (R Core Team, 2022), and converted into raster stacks before being similarly combined with elevation data through resampling.

In order to reduce computational time, a map extent for each set of tree data was created. This extent was proportional to the extent of tree data points plus a buffer, which was calculated by taking the difference of the maximum longitude/latitude and minimum longitude/latitude over two. If the maximum latitude of a tree species was at 37.6° and the minimum was at 28.4°, the buffer would be an additional ((37.6 – 28.4) / 2) or 4.6 (~500 km) extension around the points. This extent was used in extracting bioclimatic variables for testing and training the Maxent model.

Maxent Modeling

Maxent is a favourable algorithm many ecologists have utilised for creating species distribution models using presence-only data – employed for invasive pests (Munro et al., 2022), niche tree species (Grossman, 2021; Jian et al., 2022), and over 100 under-sampled plant species (Breiner et al., 2015). The principle behind Maxent lies in the 'maximum entropy principle' as defined by Jaynes (1957) in that approximating an unknown probability distribution is best accomplished when satisfying the overt constraints surrounding that distribution – leaving behind the maximum amount of entropy (or 'disorder') that is used to make inferences about incomplete data (Phillips et al., 2006). Maxent needs presence-only data, unlike other models that require data detailing absence of occurrences as well – such as Generalized Linear Models (Phillips et al., 2006).

In order to evaluate the accuracy of the model, Maxent requires background points. Background points were generated randomly using the function dismo::randomPoints, which randomly samples points within a specified extent whilst being mindful not to sample points within the same cell that 'presence' points occupy (Hijmans et al., 2021). The number of points was equivalent to that of presence points and were derived within the map extent (proportional to original distribution) for species endemic to China, and were set to 1000 for North American species. Each model was evaluated using area under the curve (AUC) and then averaged to return a final AUC score for each species. Bioclimatic variables that contributed more than 5% on average (through each iteration of Maxent) were included in the final model to be used for predictions. A table detailing the average bioclimatic variable contribution alongside final AUC score is available in the Appendix.

4. Results

For modelling Asian *Acer* species (*A. griseum* and *A. pentaphyllum)* a bootstrap method was employed; all observations but one were analyzed with the Maxent algorithm multiple times over. For example, 28 *A. pentaphyllum* observations were used to train the model, and the remaining 29th observation was used to test the efficacy of the model. Then another singular *A. pentaphyllum* observation was isolated for testing, and the other 28 were used to train the model. This method allowed for a thorough analysis despite having a small data set and addressed any idiosyncratic variables that were specific to a given observation (P. Arcese, personal communication, March 9, 2022). Tree species commonly occurring in North America (*A. macrophyllum* and *A. circinatum*) were divided into 90/10 training/testing groups and replicated 30 times over.

Each *Acer* species had between two and six variables that the Maxent model determined would predict present and future distribution. Due to the similarities of SSP scenarios chosen, there were no apparent differences between SSP245 and SSP370, nor between a 2050 projection and 2090 projection. Given the variables selected by the model, *A. pentaphyllum* has a 100%

probability of surviving in the garden; *A. griseum* has a 14% probability; *A. circinatum* has a 30% probability; and *A. macrophyllum* has a 20% probability of finding the UBCBG climate suitable. The following table shows the contribution of each bioclimatic variable and elevation, and highlights the final variables to be included in each species model (Table 1).

Table 1 - Average contributions of each bioclimatic variable as determined by repeated Maxent model runs. Abbreviations are as follows: AG = *A. griseum;* AP = *A. pentaphyllum;* AM = *A. macrophyllum;* AC = *A. circinatum*. Bolded numbers indicate final variables included in the model for future predictions. The full table with results from each model run can be found in the supplementary materials.

bio variable	AG	AP	AM	AC	Description
bio1	0.01	0.00	0.15	0.66	Annual Mean Temperature
bio10	0.00	0.00	0.10	0.46	Mean Temperature of Warmest Quarter
bio11	**25.60**	**55.75**	0.20	0.07	Mean Temperature of Coldest Quarter
bio12	0.10	0.00	0.06	0.26	Annual Precipitation
bio13	0.03	0.99	0.10	0.57	Precipitation of Wettest Month
bio14	**9.57**	0.00	0.29	**6.47**	Precipitation of Driest Month
bio15	1.63	**39.93**	1.56	3.24	Precipitation Seasonality (Coefficient of Variation)
bio16	0.08	0.00	0.20	**63.13**	Precipitation of Wettest Quarter
bio17	2.63	0.84	0.04	3.89	Precipitation of Driest Quarter
bio18	0.00	0.00	1.76	0.27	Precipitation of Warmest Quarter
bio19	0.30	0.15	**73.76**	0.95	Precipitation of Coldest Quarter
bio2	**10.54**	0.00	0.22	0.78	Mean Diurnal Range (mean of monthly (max temp - min temp))
bio3	4.42	2.12	0.18	0.42	Isothermality (bio2/bio7)x100
bio4	4.27	0.00	0.75	0.08	Temperature Seasonality (standard deviation x 100)
bio5	1.04	0.11	0.80	0.94	Max Temperature of Warmest Month
bio6	**12.93**	0.09	**11.23**	2.78	Min Temperature of Coldest Month
bio7	0.09	0.00	0.65	**9.93**	Temperature Annual Range (bio5 - bio6)
bio8	0.61	0.03	0.79	0.18	Mean Temperature of Wettest Quarter
bio9	**8.39**	0.00	**6.86**	3.78	Mean Temperature of Driest Quarter
elev	**17.75**	0.00	0.29	1.16	Elevation derived from SRTM downloaded from Worldclim
FINAL AUC	0.95	0.877	0.986	0.976	

Acer griseum

Variables that contributed more than 5% on average were selected for the final *A. griseum* model (Table 1). These included Mean Temperature of the Coldest Quarter (25.60%), Elevation (17.75%), Minimum Temperature of the Coldest Month (12.93%), Mean Diurnal Range (10.54%), Precipitation of the Driest Month (9.57%), and Mean Temperature of the Driest Quarter (8.39%). The final AUC for this model was 0.950. Based upon this result, *A. griseum*'s habitat was determined by drier and colder areas as well as elevation, which ranged from 30 m – 2018 m. Figure 3 shows the distribution of the average temperature of the coldest quarter for *A. griseum* as it exists presently; a clear preference for temperatures just around 7°C, but tolerating up to -40°C (Figure 4). The vertical lines indicate UBCBG's present climate (green) and 2090 climate under SSP245 (blue) and SSP370 (red). Bio11 (Mean Temperature of the Coldest Quarter) contributed the most to the model (25.60%) and the predicted average temperature of the coldest quarter for the Garden shows it will be more suitable in the future for this variable. However, the model still predicts an overall probability of 14% that UBCBG will be suitable for *A. griseum* given all six climatic variables represented in the model (Figure 5).

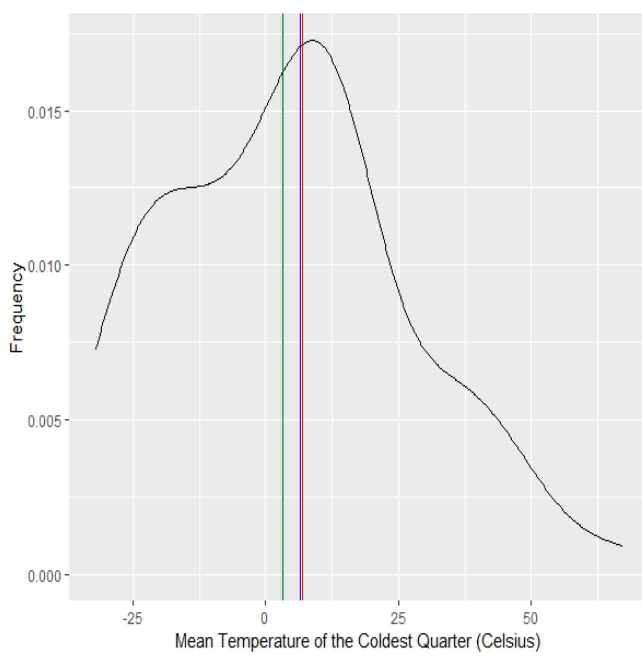

Figure 3 - Mean Temperature of the Coldest Quarter (bio11) values extracted from 'present climate' for *A. griseum,* including markers for present UBCBG value (green) and future UBCBG values under SSP245 (blue) and SSP370 (red)

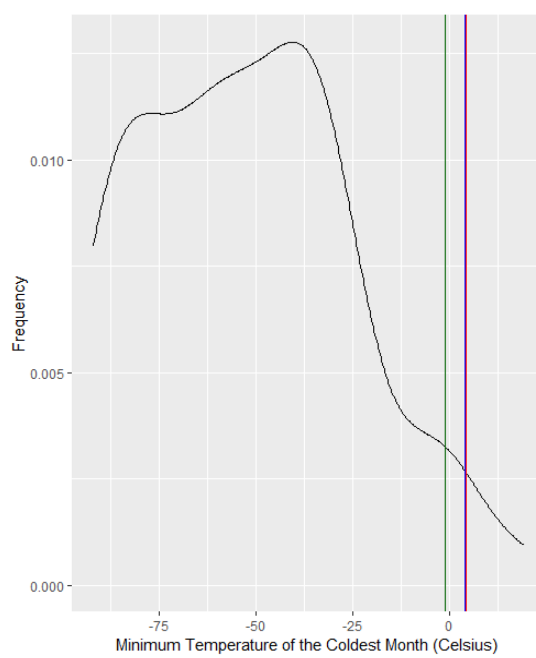

Figure 4 - Minimum Temperature of the Coldest Month (bio6) values extracted from 'present climate' for *A. griseum*, including markers for present UBCBG value (green) and future 2090 UBCBG values under SSP245 (blue) and SSP370 (red).

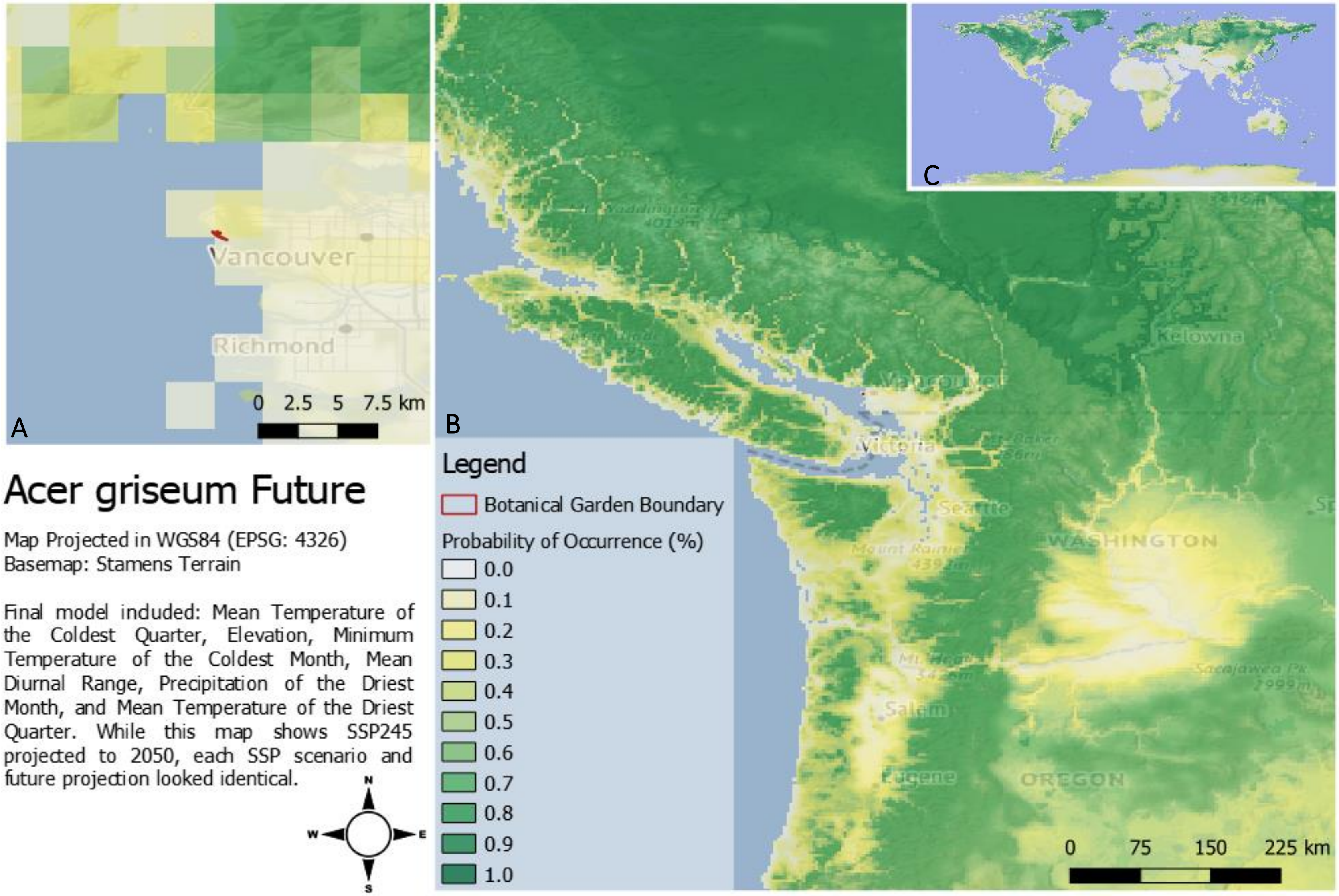

Figure 5 - Map of final probability of *A. griseum* distributions at a hyper local (A), regional (B), and global scale (C) showing the probability of occurrence. UBCBG is delineated in a red polygon shape. Darker green shows higher probability (100%) while less shows closer to 0%. *A. griseum* has a ~14% probability of finding the climate at UBCBG suitable in the future; both SSP scenarios and future projections looked identical to this distribution. Map projection is WGS84.

Acer pentaphyllum

Variables that contributed more than 5% on average were selected for the final *A. pentaphyllum* model (Table 1). The Maxent model indicated only two variables determined distribution for *A. pentaphyllum*: Mean Temperature of the Coldest Quarter (55.75%) and Precipitation Seasonality (39.93%). The final AUC for this model was 0.877. Based upon this result, the distribution for *A. pentaphyllum* was largely determined by cold temperature (Figure 6) and precipitation seasonality. Precipitation Seasonality can be understood as the amount of deviation from a 'normal' amount of precipitation that each month exhibits over the course of the year (O'Donnel & Ignizio, 2012). Figure 6 shows the distribution of the average temperature of the coldest quarter for *A. pentaphyllum* as it exists presently; the curve can be seen as normally distributed with most trees occupying a location where the average temperature for the coldest quarter is around 2°C. The vertical lines indicate UBCBG's present climate (green) and 2090 climate under SSP245 (blue) and SSP370 (red) and show that the climate for UBCBG in the future will still be suitable for *A. pentaphyllum.* Given the climatic variables represented in the model, maxent predicted a 100% probability of UBCBG being suitable for A. pentaphyllum. It is worth noting that modelling with occurrence data less than 30 points may result in an over-fit model (Breiner et al., 2015) and a distribution that predicts suitable climate in more places than is realistic. This is the likely reason why the model predicted *A. pentaphyllum* will find most of the world suitable in the future (Figure 7).

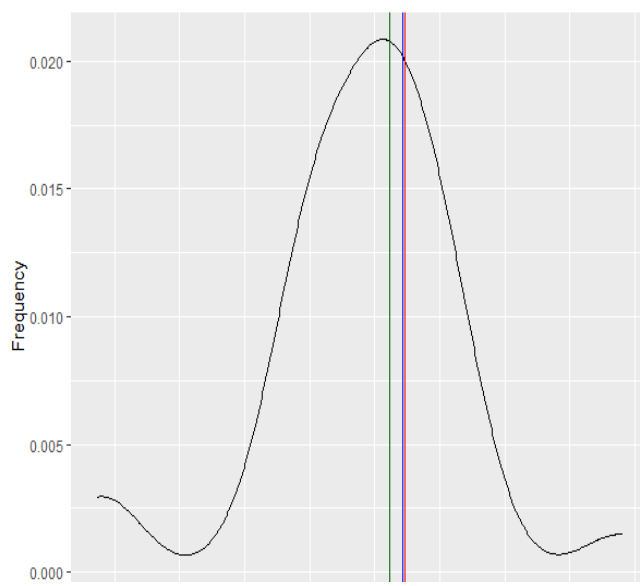

Figure 6 - Mean Temperature of the Coldest Quarter (bio11) values extracted from 'present climate' for *A. pentaphyllum*, including markers for present UBCBG value (green) and future UBCBG values under SSP245 (blue) and SSP370 (red).

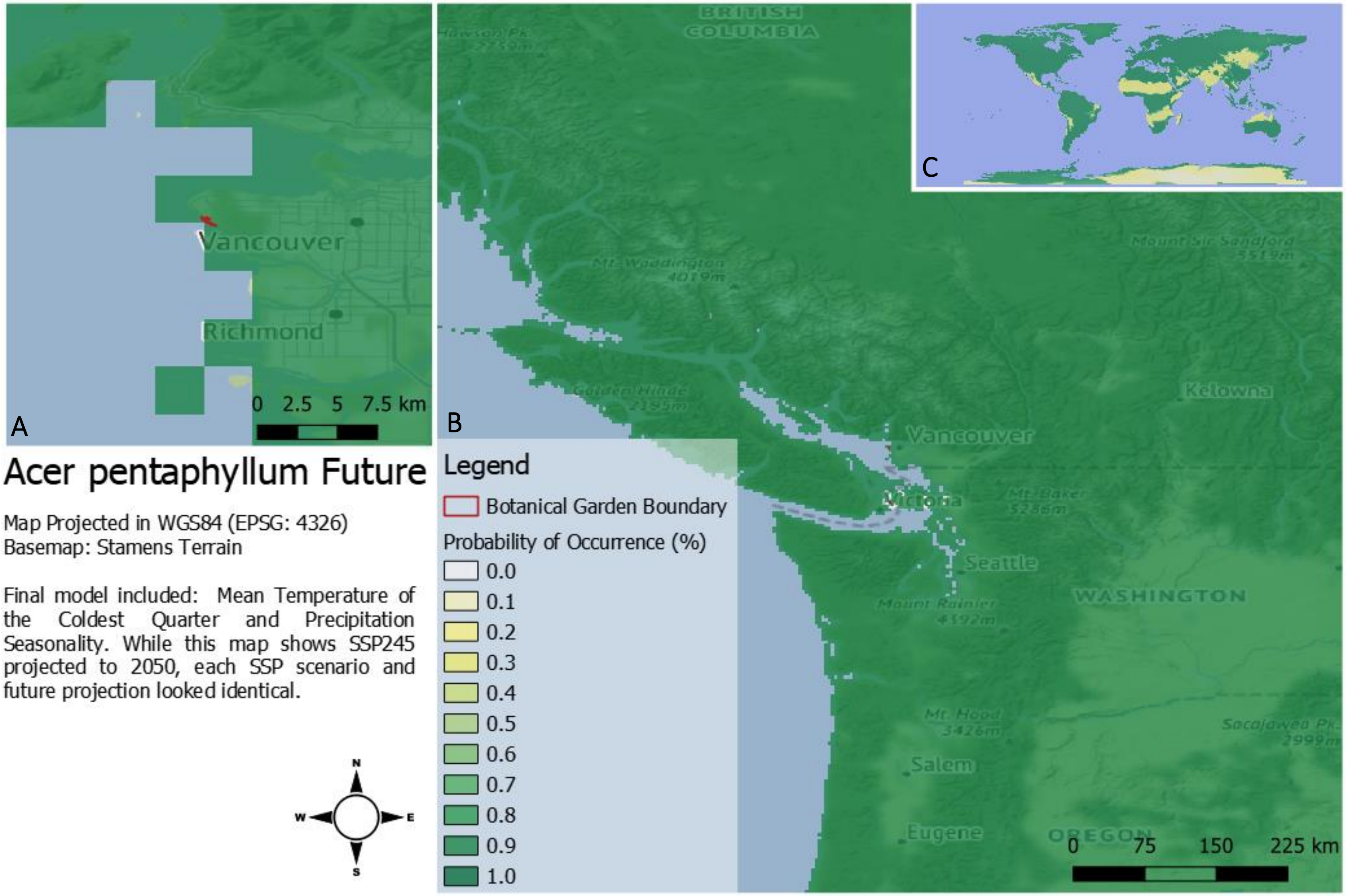

Figure 7 - Map of final probability of *A. pentaphyllum* distributions at a hyper local (A), regional (B), and global scale (C) showing the probability of occurrence. UBCBG is delineated in a red polygon shape. *A. pentaphyllum* has a 100% probability of finding the climate at UBCBG (and the rest of the world) suitable in the future; both SSP scenarios and future projections looked identical to this distribution. Map projection is WGS84.

Acer macrophyllum

Maxent was ran approximately 30 times with 90% of the data training the model and 10% testing the efficacy. Variables that contributed more than 5% on average were selected for the final *A. macrophyllum* model. These included: Precipitation of the Coldest Quarter (73.76%), Minimum Temperature of the Coldest Month (11.23%), and Mean Temperature of the Driest Quarter (6.86%). The final AUC for this model was 0.986. The figure below shows the distribution of Precipitation of the Coldest Quarter (73.76% contribution to the model) for *A. macrophyllum* in its present climate, as well as UBCBG's future increase of precipitation over the coldest quarter (Figure 8). This shows that, while UBCBG has a relatively suitable precipitation value in its current climate (500 mm of precipitation), the 2090 future scenarios predict precipitation amounts closer to ~600mm, and therefore not favourable for *A. macrophyllum*. With all three climate variables included, the model predicted an overall 20% probability that *A. macrophyllum* will find the UBCBG climate suitable in the future (Figure 9).

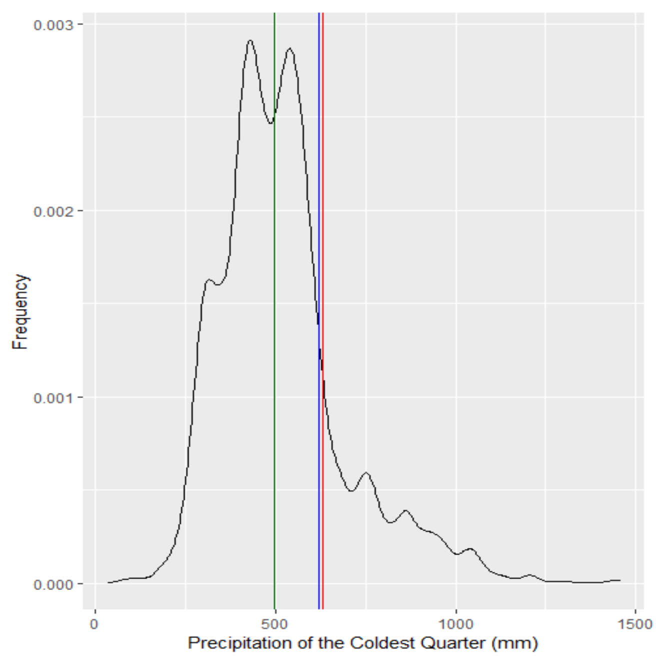

Figure 8 - Precipitation of the Coldest Quarter (bio11) values extracted from ''present climate' for *A. macrophyllum*, including markers for present UBCBG value (green) and future UBCBG values under SSP245 (blue) and SSP370 (red)

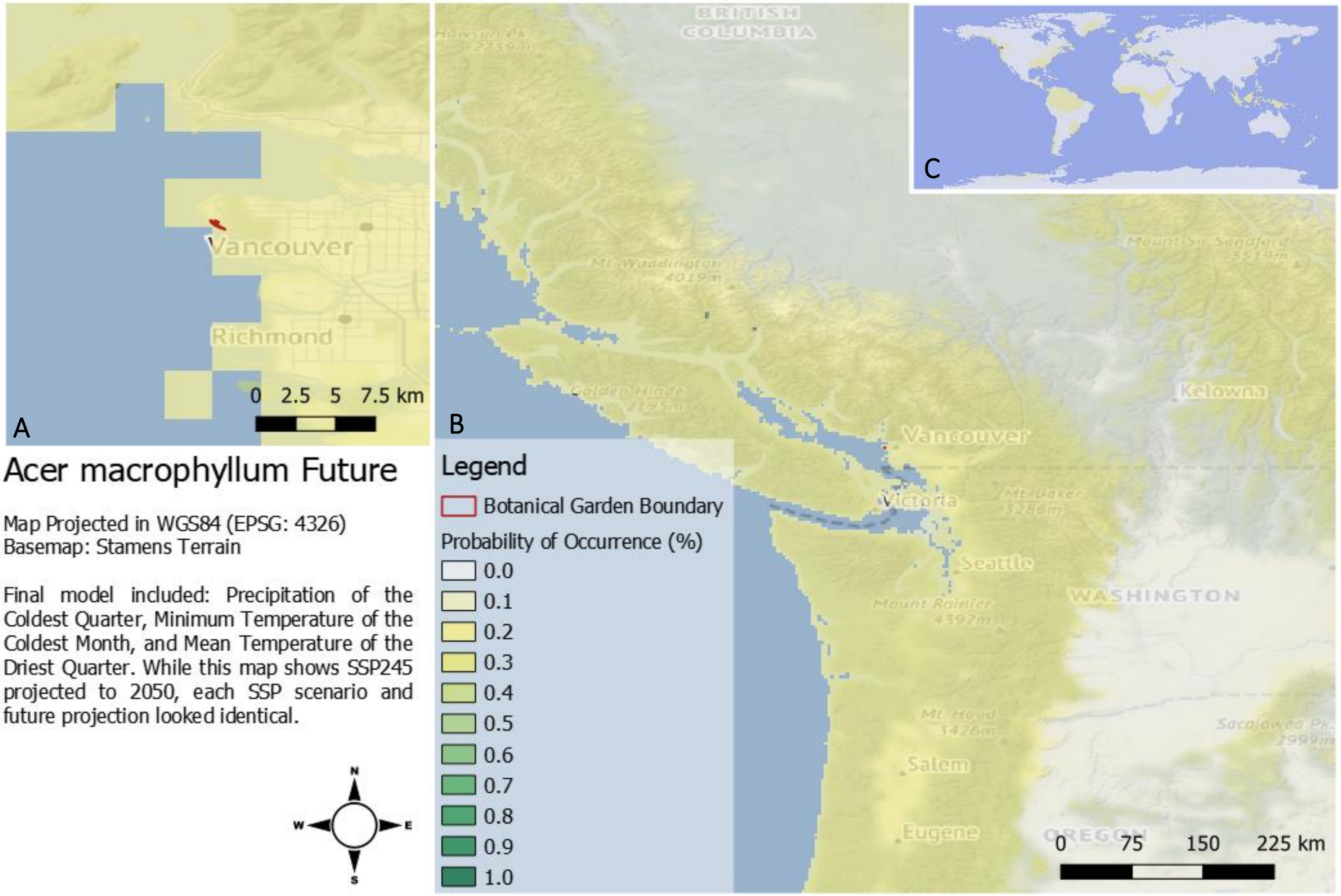

Figure 9 - Map of final probability of *A. macrophyllum* distributions at a hyper local (A), regional (B), and global scale (C) showing the probability of occurrence. UBCBG is delineated in a red polygon shape. *A. macrophyllum* has a 20% probability of finding the climate at UBCBG suitable in the future; both SSP scenarios and future projections looked identical to this distribution. Map projection is WGS84.

Acer circinatum

Maxent was ran approximately 30 times with 90% of the data training the model and 10% testing the efficacy. Variables that contributed more than 5% on average were selected for the final *A. circinatum* model. These included: Precipitation of the Wettest Quarter (63.13%), Temperature Annual Range (9.93%), and Precipitation of the Driest Month (6.47%). The final AUC for this model was 0.976. The figures below show the distribution of *A. circinatum's* current climatic values for precipitation of the wettest quarter (Figure 10) and precipitation of the driest month (Figure 11). It is evident that the current climate at UBCBG (green line; Figure 10) is favourable for *A. circinatum*, as the peak distribution is near 600 mm and present UBCBG climate is a little less than that. However, as the climate changes and more precipitation occurs, the values for UBCBG fall further on the curve and outside an optimal/suitable threshold (Figure 10). Similarly, Figure 11 shows the present climate being closer to the largest peak in the distribution, and future scenarios moving further away, indicating less suitability in the future under either scenario. When including all variables, the model predicted a 30% probability of *A. circinatum* finding UBCBG suitable in the future under either scenario.

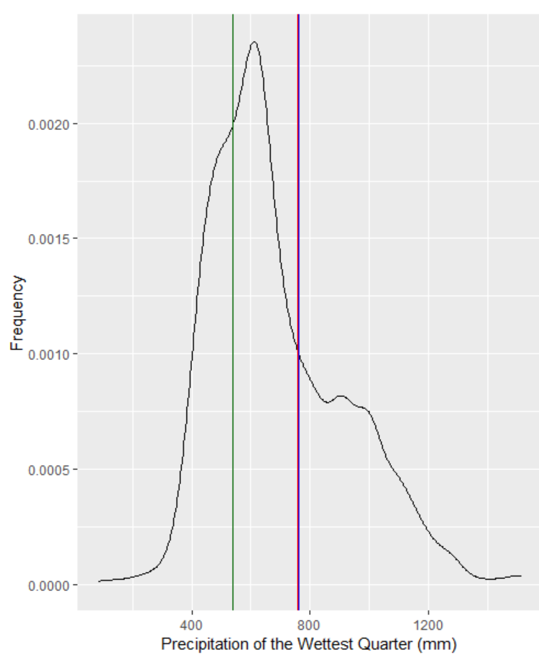

Figure 10 - Precipitation of the Wettest Quarter (bio16) values extracted from ''present climate' for *A. circinatum*, including markers for present UBCBG value (green) and future UBCBG values under SSP245 (blue) and SSP370 (red)

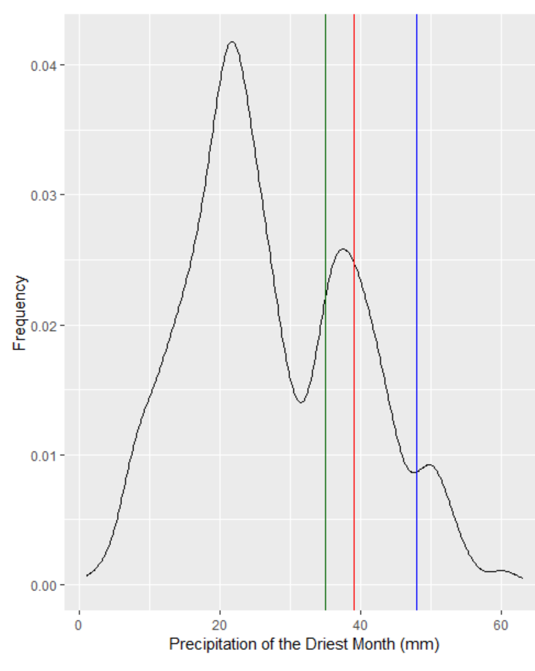

Figure 11 - Precipitation of the Driest Month (bio14) values extracted from ''present climate' for *A. circinatum*, including markers for present UBCBG value (green) and future UBCBG values under SSP245 (blue) and SSP370 (red)

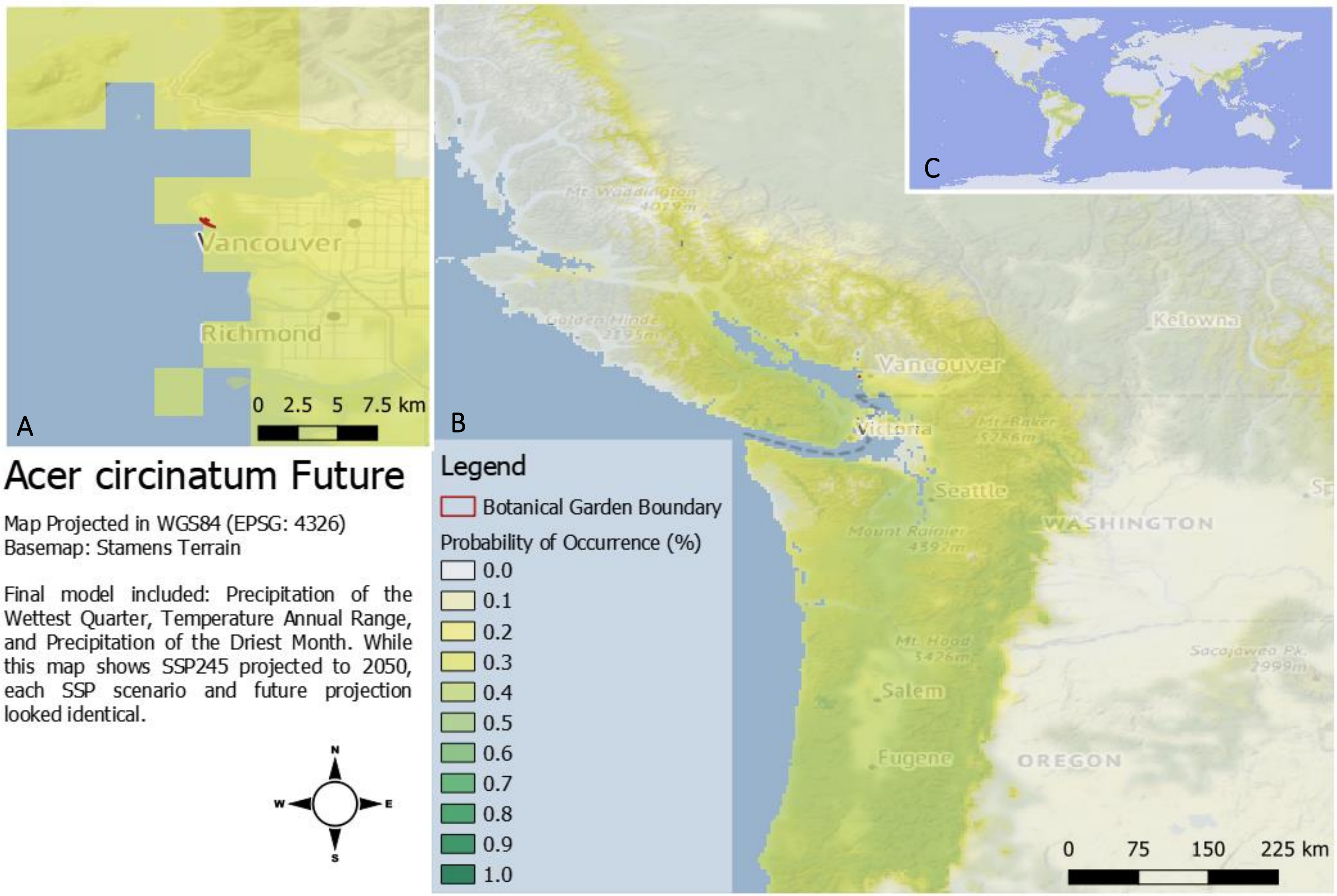

Figure 12 - Map of final probability of *A. circinatum* distributions at a hyper local (A), regional (B), and global scale (C) showing the probability of occurrence. UBCBG is delineated in a red polygon shape. *A. circinatum* has a 30% probability of finding the climate at UBCBG suitable in the future; both SSP scenarios and future projections looked identical to this distribution. Map projection is WGS84.

5. Discussion

This study determined the climatic suitability of UBCBG for two North American Acer species listed as least concern: *A. circinatum*, and *A. macrophyllum*; which had a probability of 30% and 20% (respectively) of finding UBCBG suitable. This study also determined the climatic suitability for two Asian species listed as critically endangered and endangered in the The Red List*:* *A. pentaphyllum* and *A. griseum;* which had a probability of 100% and 14% (respectively) of finding UBCBG suitable. The importance of this research can go on to inform UBCBG on further conservation strategies and management. The 'Botanic Gardens Conservation Strategy' was published in 1989 and articulated Botanical Gardens should be defined as preservers of collections - particularly endangered and critically endangered species - and document collections for the purpose of scientific research, horticulture, conservation, plant introduction, display, sustainability, education, and outreach (Heywood, 2017). Furthermore, with sufficient resources and communication, Gardens have the ability to integrate conservation focused on individual regions (Westwood et al., 2021); recognizing that some species will no longer successfully thrive in present environments, and other species may come to find new environments suitable for cultivation (Heywood, 2017). The results from modelling four species of *Acer* should be scrutinized and replicated before making any firm decisions towards conservation, seed banking, and relocation of trees not finding UBCBG suitable (ie *A. griseum, A. macrophyllum, A. circinatum*). However, the methodology is sound and the available code (supplemental material) is abstract enough to apply the considerations listed below (see section: *Limitations*) with any species, future climate scenario, and different future-predicting global circulation model.

<u>Model Qualitative Evaluation</u>

Asian Trees

There is scarce literature available for both *A. pentaphyllum* and *A. griseum* of which we can compare the results of this study to. Grossman's evidence of constrained divergence study did examine *A. griseum* but noted that *A. pentaphyllum* was deliberately not included due to lack of publicly available data (2021). Other literature surrounding either species often details collection endeavors and expeditions (eg. Del Tredici, 2015; McNamara, 2011) and genomic sequencing (eg. Areces-Berazain et al., 2021; Dai et al., 2020; Sun et al., 2014). The latter place *A. pentaphyllum* and *A. griseum* in 'sister clades', indicating more shared genomic traits between the two than most other *Acer* species (Areces-Berazain et al., 2021; Dai et al., 2020). It may be speculated that these genomic similarities are behind the similar variable selection shown in this study, as both *A. griseum* and *A. pentaphyllum* had bio11 (Mean Temperature of the Coldest Quarter) contribute the most to their respective Maxent models. However, while this is the only similarity both species shared from this study, Grossman's Maxent analysis of *A. griseum* showed bio15 (Precipitation

Seasonality) having a permutation importance of 80% to his model (Table S3 in Grossman, 2021). In this study*, A. pentaphyllum's* final distribution was determined by both bio11 (shared with *A. griseum* per this study) and bio15 (shared with *A. griseum* per Grossman's study), though further research (with more data or alternative methods; see *Limitations: Presence-only Data*) must be done to determine if these factors truly determine the distribution of this species or if further abiotic features contribute to the distribution of either Asian-endemic species.

Other studies examine factors beyond bioclimatic variables with varying importance. Wu et al. also consider soil organic carbon, soil pH, vapor pressure, wet-day frequency, and UV-B seasonality in their model for *Acer truncatum* Bunge and reveal UV-B contributed 8% to the species distribution (2021); another study considers coenoecological differentiation (surrounding vegetation and ecological community) and discovers all four *Acer* trees of interest (*Acer campestre* L., *Acer platanoides* L., *Acer pseudoplatanus* L., *Acer tataricum* L.) occur in the same vegetation grouping (Kabaš et al., 2014). Future studies should consider similar variables as that mentioned in Wu et al. (2021) as well as canopy cover, soil compactness, soil nutrients/minerals, surrounding vegetation, slope, aspect, proximity to water bodies, and/or proximity to urban areas.

North American Trees

Unlike *A. griseum* and *A. pentaphyllum*, the variables included in the final models for *A. macrophyllum* and *A. circinatum* share no similarities whatsoever. *A. macrophyllum* appears largely defined by 'coldness', having bio19 (Precipitation of the Coldest Quarter) and bio6 (Minimum Temperature of the Coldest Month) as most contributing variables. *A. circinatum*, however, can be largely defined by quantity of precipitation (~90% in the final model) followed by 10% variable contribution from Temperature Annual Range (bio7). However, neither species are anywhere near each other in the *Acer* phylogenetic tree – in fact, Grossman (2021) shows that these species converged from their shared ancestor roughly 50 million years ago.

When considering that the model for *A. macrophyllum* largely depended on 'coldness', and adding the perspective that future climate scenarios anticipate a warming between 2.0 – 3.7°C (IPCC, 2021), it makes sense that Maxent estimates *A. macrophyllum* to have a 14% probability of suitability. While this result is grim, it is pertinent to recall that Maxent's conclusions are strictly drawn on that which it is fed – which is to say that Maxent has no information regarding current conservation practices and protected areas, nor degrees of adaptation/migration that *A. macrophyllum* or *A. circinatum* have already undergone (as Botkin et al., (2007) point out, there has been very few species that have gone extinct due to global warming since the last ice age). Therefore, the Maxent model's assumption is that both *A. macrophyllum* and *A. circinatum* will suffer in future climates so long as there is no migration/adaptation attempts from either species. One study shows that integrating both adaptation and migration into future forecast modeling protects roughly 50 populations that would otherwise be lost in a scenario where no adaptation and no migration happened (Hamann & Aitken, 2013). While protected populations still trended negatively as time passed, Hamann & Aitken's study show the importance of including 'best-case' and 'worst-case' scenarios in species distribution forecasts so that conservation planning can act under an optimistic or pessimistic scenario (2013).

Lastly, similar to geographic criticism addressed above regarding *A. griseum* and *A. pentaphyllum*, the geographic extent of *A. macrophyllum* and *A. circinatum* should have been limited to that which is similar to the region of interest. This would capture the specific ecological niche being sought after, as the range of temperature and precipitation covering the true distribution of either species is large and highly variable.

<u>Limitations</u>

Presence-only Data

Due to their 'endangered' and 'critically endangered' status, observations for *A. griseum* and *A. pentaphyllum* were less than 100. Breiner et al. (2015) note that this can cause issues in modeling as species with low occurrence data (< 30) and a large number of explanatory variables can result in over-predicting environmental suitability. While stepwise selection of variables can be employed to limit this issue (as we used in this study by the Maxent replication) the model still needs validation by segmenting the data and creating a 'testing' and a 'training' group. In small occurrence datasets, this often means training the model with 18 predictors and testing it with 2, which is not sufficient for capturing the true ecological niche the species occupies (Breiner et al., 2015). Breiner et al. (2015) found that creating ensembles of small models (ESMs) had significantly better prediction accuracy than standard species distribution models such as Random Forest, Maxent, Generalized Linear Models, etc. Future endeavors regarding predicting distribution of either *A. pentaphyllum* or *A. griseum* should utilize the ESM methodology described in Breiner et al. (2015) as the results from that study proved more accurate distribution the rarer (less recorded) the species became.

Maxent essentially estimates the probability of occurrence in a given geographical space with changing parameters (ie climate) (Elith et al., 2011) and returns the odds of that geographical space of occupancy being suitable in the future. This study, however, changed both climatic parameters *and* geographic location, by using presence-only data over China and estimating probability for an external location. This forces the assumption that the abiotic forces tangential to climate (wind force, rain water composition, soil nutrient density, seasonal daylight oscillations, etc) are equivalent for both sites. This is a large and, frankly, very wrongful assumption. Future studies that wish to avoid making this assumption should gather data of *A. griseum* and *A. pentaphyllum* as they exist *presently* in the geographical location of interest (i.e. Vancouver, BC, for this case study) as opposed to extrapolating across two very different geographical locations.

Global Climate Model (GCM)

This study only considered one GCM (MIROC-ESL2L) at a resolution of ~5 km^2. Species distribution studies often incorporate multimodal ensembles that include many global circulation models averaged together (Evans et al., 2011; Jian et al., 2022) as individual global circulation models are highly variable and subject to bias. As discussed earlier, MIROC-ESL2L is an extension of the MIROC model, newly incorporating biogeochemical processes like carbon-nitrogen interactions that account for soil nutrient control over plant growth (Hajima et al., 2020). However, MIROC-ESL2L exhibited a 32% reduction of transient climate response to cumulative carbon emissions compared to an average of the Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Models, suggesting a more 'optimistic' simulation of carbon cycle changes (Hajima et al., 2020). Future studies should incorporate multiple GCMs and seek a finer resolution, as ~5 km^2 represented the majority of Vancouver, BC rather than the niche climate at UBCBG (Note: At the time of this study, future climate scenarios at a 30s resolution were not available). One excellent resource is Tongli Wang's ClimateNA, which locally downscales historical and future climate layers into scale-free estimates for all of North America and provides annual, seasonal, and monthly climatic estimates (Wang, Hamann, et al., 2016). This application is also available for regions over Asia-Pacific (Wang, Wang, et al., 2016) and utilizes over 10 GCMs in extracting climatic variables.

6. Future Directions

In short, future studies should utilize other variables beyond the 19 bioclimatic variables and elevation that were employed in this study. These studies should also strive to use presence data that is within the geographical area of interest as opposed to extrapolate extent and make assumptions about two very different geographical locations. Smaller datasets should look into employing ensembles of small models (ESMs) as demonstrated in Breiner et al., (2015). Larger datasets (>1000 records) should be critically examined for occupying multiple ecoregions and divided appropriately prior to analysis. In a conservation context, incorporating scenarios that acknowledge adaptation and migration can best inform policy on which species are deserving of more attention. Lastly, multiple global circulation models should be utilized in making future predictions of species distribution, lest a single model's bias is overtly optimistic or pessimistic in its projection.

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