Modelling the Potential Impacts of Climate Change on Arboreal Diversity of the UBC Vancouver Campus from 2050 to 2080

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Abstract

Climate change poses a considerable risk to forest diversity in urban communities. The University of British Columbia (UBC) seeks to identify vulnerable tree species on campus and apply strategies for sustaining arboreal diversity in future decades. In contribution to these efforts, this study investigated the potential shift in tree composition on the UBC Vancouver Campus over the next century by (1) predicting suitable climatic habitat for 128 campus species in 2050 and 2080, and (2) mapping the expected change in species richness across North America. Species distribution modelling was performed to define the current range of temperature and precipitation conditions for each tree species. The ranges were projected into RCP 8.5 worst-case climate scenarios for 2050 and 2080 as defined by the Intergovernmental Panel on Climate Change. Results indicate that climate change is expected to have a substantial impact on suitable habitat for trees on the UBC campus; 32% of the species are projected to lose their suitable climatic conditions on campus by 2080. On average, species ranges are projected to shift northwards by 8.1º (~ 900 km) in the coming century from 40.7º N to 48.7º N. Species estimated to have the greatest range shift such as silver birch (*B. pendula*) may require careful maintenance, or replacement with species of similar ecological function in the future. This study highlights the urgency of climate-induced habitat decline at UBC Vancouver and provides insight for a 'Trees and Biodiversity' strategy to restore and enhance arboreal diversity.

Keywords: urban forestry, climate change, habitat suitability, biodiversity, species distribution models, ensemble forecasting.

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1. Introduction

1.1 *Context*

Over the next century, climate change is expected to have a negative impact on global forest health and diversity (Allen et al., 2010). The consequences of climatic shift are particularly severe for natural and urban forests comprised of tree species that are susceptible to environmental change (Potter et al., 2017). In recent decades, tree mortality rates have accelerated due to direct climate change impacts such as elevated temperatures and drought conditions in western North America (Daniels et al., 2011). Regions of highest vulnerability to drought appear across western and central Canada, where climatic shifts are predicted to exceed local tolerances by mid-century and greater distances to suitable habitat will inhibit migration capacity (Aubin et al., 2018). Several projections predict a high risk of mortality events for forests in 2100 drought and temperature scenarios (Adams et al., 2017; Allen et al., 2010).

As the climate crisis impacts forest health and mortality rates, it will inevitably affect the ecosystem services provided by trees. For instance, trees offer protection against the negative effects of climate change through carbon sequestration and flood control (Demuzere et al., 2014; Rötzer et al., 2019). Urban tree mortality may result in losses of natural habitat, biodiversity and ecosystem services that regulate air quality, surface runoff and soil moisture in cities (Anderegg et al., 2013; Gómez-Baggethun et al., 2013). The loss of ecosystem services is especially prominent in areas of urban expansion, where development continues to reduce available vegetation cover (Carvalho et al., 2019). Communities exposed to the risk of rising temperatures and flooding will become increasingly vulnerable as these effects are exacerbated by the loss of regulating services (Gill et al., 2007). It is essential to protect urban forests and their ecosystem services which will help mitigate the adverse impacts of climate change.

To date, more research has been done on regional impacts of climate change on forests compared to local scale studies relevant to vulnerable communities. Unlike regional trends, local scale impacts are highly content-dependent and elicit a need to examine climate change impacts by specific case scenarios (Vellend et al., 2017). Local scale studies will become increasingly important as cities and institutions develop biodiversity management strategies to enhance climate resilience. For example, the University of British Columbia (UBC) campus plan will be amended to include a biodiversity strategy in the next decade (UBC, 2015). Monitoring and increasing carbon sequestration of campus trees will also be beneficial to the Climate Action Plan 2030 for achieving net zero emissions by 2050 (UBC, 2021). Forming appropriate policy will require information on how the institution should manage their urban forests, to retain ecosystem benefits and mitigate climate change impacts on the campus community (Matthews et al., 2013). One way to address this knowledge gap is to investigate how the UBC urban forest composition is expected to change in the next several decades, particularly in mid-century (2050) and late century (2080) scenarios. By determining the tree species that are most vulnerable to climate-induced habitat loss, the ecosystem services they provide could be identified and emphasized in plans to enhance the urban forest of UBC Vancouver.

1.2 *Objectives*

To investigate the impact of climate change on tree diversity at UBC Vancouver, I determined the tree species that are projected to lose their suitable climatic niche on campus from 2050 to 2080. As reference, many studies have utilized species distribution modelling techniques to forecast tree habitat ranges in the future (Pecchi et al., 2019). For example, Dyderski et al. (2017) predicted ranges for 12 European forest tree species in the years 2061-2080, and Garcia et al. (2013) modelled the distribution of 14 threatened forest species in the Philippines for the years 2011-2040. Both studies used the species distribution modelling tool MaxEnt (Phillips et al., 2006) and determined a subset of tree species which were most likely to lose suitable habitat over their current ranges. Guided by these case studies, I first obtained a complete list of species from the UBC campus tree inventory to represent the baseline tree composition of campus. For each species, I used occurrence data of its distribution across North America to model the range of temperature and precipitation conditions tolerated by the species. The models were evaluated and used to project the species ranges into future climate scenarios in 2050 and 2080.

From the projected species distributions, I identified tree species which no longer have suitable habitat within the campus extent and observed expected changes in species richness over time. Similar to Lim et al. (2018) which modelled future forest diversity on the Korean Peninsula, I created species diversity maps for 2050 and 2080 by overlaying and adding the species distributions that will retain suitable habitat on campus. This indicates the exposure of campus tree species to heat and drought stress, an aspect of their vulnerability to climate change. The study indicates the total number and composition of species that could pass their niche thresholds in the next decades. From the species that are found to be most vulnerable to climate-induced mortality in the future, we could determine what the potential losses in ecosystem services are and highlight the urgency of the issue for campus planning policy. This study will inform landscape design decisions and influence the development of a ‘Trees and Biodiversity’ policy in the upcoming campus plan amendment. By determining the extent at which projected climate shifts will impact the UBC community, there can be recommendations made for biodiversity protection.

I hypothesize that there will be losses in tree diversity on the UBC Vancouver campus from now to the end of the century, due to increased vulnerability of trees that are of particular species types, ages, or conditions (Hilbert et al., 2019). Even in the current baseline condition, there are several tree types in western British Columbia that are under threat of decline due to direct and indirect climate change impacts. For example, conifers and coastal old growth forests are threatened by drought, heat and loss of suitable habitat due to changing conditions (Daniels et al., 2011; Hamann et al., 2006). As a result, the campus community may lose regulating ecosystem services like carbon storage, air filtration, mitigation of the urban heat island effect, UV protection and storm water management, many of which are canopy dependent (Clapp, 2014). The results of this study will provide recommendation on which tree species might need to be replaced in the future, ideally with species that are more tolerant to shifting conditions and have similar ecological functions. Results can also be useful to guide tree-planting initiatives that optimize desirable ecosystem benefits, as done by Bodnaruk et al. (2017). This study will increase awareness of urban forest decline on the UBC Vancouver campus predicted to occur several decades beyond 2021.

2. Study Site and Data Description

2.1 *Study site*

The University of British Columbia Vancouver Campus (49.2606° N, 123.2460° W) is situated on the western tip of Point Grey Peninsula in British Columbia, Canada (Figure 1).

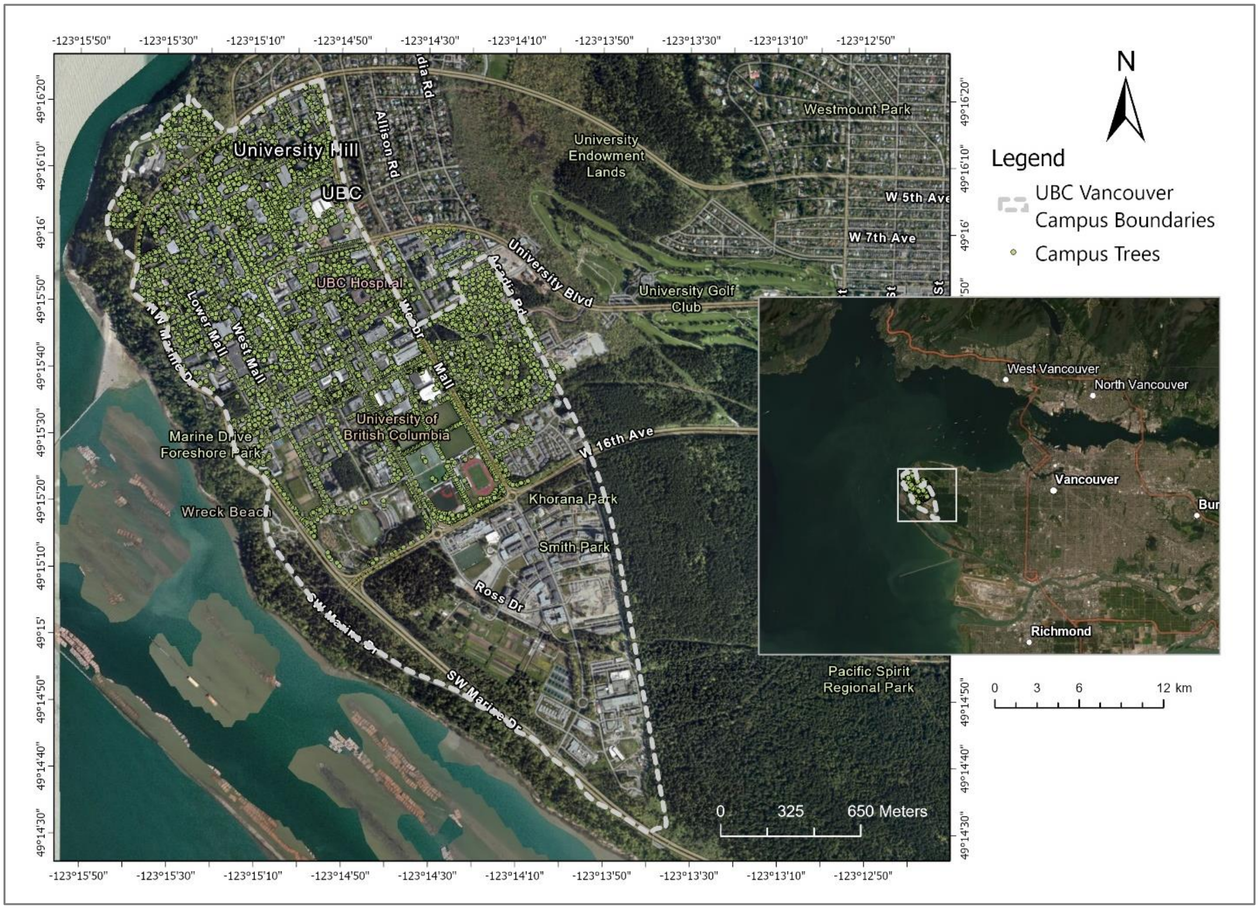

Figure 1. The University of British Columbia Vancouver Campus is surrounded by dense protected forests in Point Grey, BC; trees within its borders are carefully managed to prevent further decline to urban development and climate stressors. Available tree inventory data (Burton & Wiersma, 2016) cover the upper campus area interspersed with academic land use. Base imagery is projected in NAD 1983 UTM Zone 10N and sourced from ESRI, OpenStreetMap contributors and the GIS User Community (2021).

Located approximately 9.5 km from downtown Vancouver, the area is dominantly surrounded by the Pacific Spirit Regional Park and was originally set in a clearing of conifer forest (Sutherland, 2017). The campus was established in 1908 and has since expanded its urban coverage of buildings, roads and open vegetation (UBC Campus & Community Planning, 2015). It currently covers an area of 4.020 km^2 and incorporates a variety of academic and natural land use types (UBC Campus & Community Planning, 2014). In recent decades, the development of neighbourhood housing communities has driven more than a 24% decline of tree canopy on campus, with the greatest losses in conifer cover (Sutherland, 2012). Including the UBC Botanical Gardens and UBC Farm, about half (2.044 km^2) of the total campus area now consists of vegetation features such as grass, planting beds and trees (Burton & Wiersma, 2016). The university has managed its urban forest of over 10 000 native trees since 1925, and has planted approximately 8,000 trees (UBC Campus & Community Planning, 2015).

The campus is situated in the Coastal Douglas-Fir biogeoclimatic zone within the Moist Maritime Subzone, suitable for temperate mixed woods (British Columbia Forest Service, n.d.). Coastal old growth forests from over 250 years ago line the southwest sides of campus, including species such as Douglas fir (*P. menziesii*), grand fir (*A. grandis*) and big leaf maple (*A. macrophyllum*) (Sutherland, 2017). A diverse set of deciduous species as well as urban garden vegetation are interspersed with the built campus environment; a few of the most abundant tree families include maple, cypress, pine and oak. Within coniferous types, there are fewer species as western red cedar (*T. plicata*) and Douglas fir trees are dominant (Burton & Wiersma, 2016). There is a uniform climate throughout the study site, with gentle topography and an average elevation of 87 m (Google Earth, 2020). As the region lies in the rainshadow of Vancouver Island and the Olympic mountains, there are warm, dry summers and mild, wet winters (Green & Klinka, 1994). The average high temperature in both July and August is 22.2º C, with record highs reaching 30.6 and 34.4º C respectively; during this time of year, average precipitation is relatively the lowest at 35.6 and 36.7 mm. The region experiences the mildest climate in Canada, with droughts occurring in dryer sites and increasing average annual temperatures in recent years (Environment and Climate Change Canada, 2020).

2.2 *Data description*

UBC Vancouver Campus Tree Inventory

Point locations of trees on the University of British Columbia (UBC) Vancouver campus were downloaded as a geoJSON dataset from the UBC open geospatial repository on GitHub (https://github.com/UBCGeodata/ubc-geospatial-opendata/tree/master/ubcv/landscape). The dataset contains 7000 observations for 180 distinct tree species and covers the UBC upper campus core between 123.2610-123.1960º W and 49.2793-49.2348º N (Figure 1). Data are provided in the WGS84 coordinate system. Tree attributes include a unique identifier, family, genus, species, common name, mortality status, diameter at breast height (dbh) in cm, height in m, error range of tree height in m, crown measurements and location in longitude and latitude. 4898 tree records already include the minimal required information such as location and species identification, and 2102 records solely report the location of the tree. The dataset was first made available on November 30, 2016 and is continually updated through field observations and other supplemental data sources; tree locations have been identified from 2019 orthophotos of campus and tree measurements were taken by students of the UFOR101 Urban Forestry class at UBC. Species identification was done by Egan Davis, Principal Instructor of the Horticulture Training Program at the UBC Botanical Garden. Tree heights for some trees have been derived from a 2018 LiDAR dataset of campus and have varied accuracies.

ClimateNA Dataset

Downscaled interpolated climate data at a resolution of 1 km for all of North America, generated and described by Wang et al. (2016) was retrieved from ClimateNA v5.21

(https://sites.ualberta.ca/~ahamann/data/climatena.html). Climate rasters are in the Lambert Conformal Conic projection, with a broad extent between 169.3-46.2º W and 8.6-75.3º N to model latitudinal shift in species ranges. They were downloaded in ASCII (.asc) format, with a radiometric resolution of 32-bit. The relevant bioclimatic variables for the study include mean annual temperature (°C) and mean annual precipitation (mm) for a baseline period of 1961-1990, as well as for two future projection periods: the 2050s (an average of 2041-2070) and 2080s (an average of 2071-2100). Current baseline data were derived from the CRU-TS 3.22 meteorological dataset (Mitchell & Jones, 2005) using the Parameter Regression of Independent Slopes Model (PRISM) interpolation method in 4 km resolution, resampled to 1 km cells. Averaged climate projections were created based on the Coupled Model Intercomparison Project phase 5 (CMIP5) database corresponding to the IPCC Fifth Assessment Report (2014). Of the many climate simulation models available, the model chosen for the study was an ensemble of 15 Atmosphere-Ocean General Circulation Models (AOGCMs)[1] chosen to represent major clusters of models (Knutti et. al., 2013). The projections represent the Representative Concentration Pathways (RCP) 8.5 high emissions scenario, which predicts a global average temperature increase of 2.0°C (±0.6) by the 2050s and 3.7°C (±0.9) by the 2080s. The worst-case emissions scenario was selected to determine an upper estimate of species range shift.

[1] The models include the CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO Mk 3.6, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5 and GISS-E2R. For more information on selected AOGCMs, see Knutti et al. (2013).

GBIF Species Occurrence Data

Point occurrence data for the western North American distribution of 180 campus tree species was obtained from the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/). Data at the species level were queried and retrieved by scientific name using the ‘dismo’ package in R (Hijmans et al., 2020), including only records with valid coordinates and that were contained within the approximate extent of North America between 169.3-46.2º W and 8.6-75.3º N. All records after 1961 were selected to match climatic baseline data for species distribution modelling. The data are stored in the WGS84 coordinate system in csv format with latitude and longitude columns. Point occurrence data from the GBIF worldwide repository consist of research-grade observations verified by the iNaturalist community, as well as preserved and live specimen collections from various museums, herbariums and institutions across North America. Compiled from variable sources, the biodiversity datasets adhere to the Darwin Core Standard (DwC) originally developed by the Biodiversity Information Standards (TDWG) community for consistent attribute definitions and formatting (Darwin Core Task Group, 2009). The number of point observations vary widely between species and are acquired throughout the year, with more observations occurring in the summer months.

3. Methods

3.1 *Overview*

Using the acquired species occurrence and climate data, I performed distribution modelling for tree species on the UBC Vancouver campus to predict how species diversity may change in future scenarios of 2050 and 2080. The methodology of this project was separated into three main components illustrated in Figure 2. These included (1) data pre-processing, (2) species distribution modelling and evaluation, and (3) deriving species richness on campus. Batch processes in ArcGIS Pro (Esri Inc., 2021) were used to automate the same steps for each species. I utilized the 'biomod2' package in R (R Core Team, 2021; Thuiller et al., 2020) to implement MaxEnt, a set of functions for environmental niche modelling and projection (Phillips et al., 2006). Overall, this analysis evaluates the response of trees on the UBC Vancouver campus to climate change across multiple decades, and estimates the amount and composition of species diversity that will remain in the future.

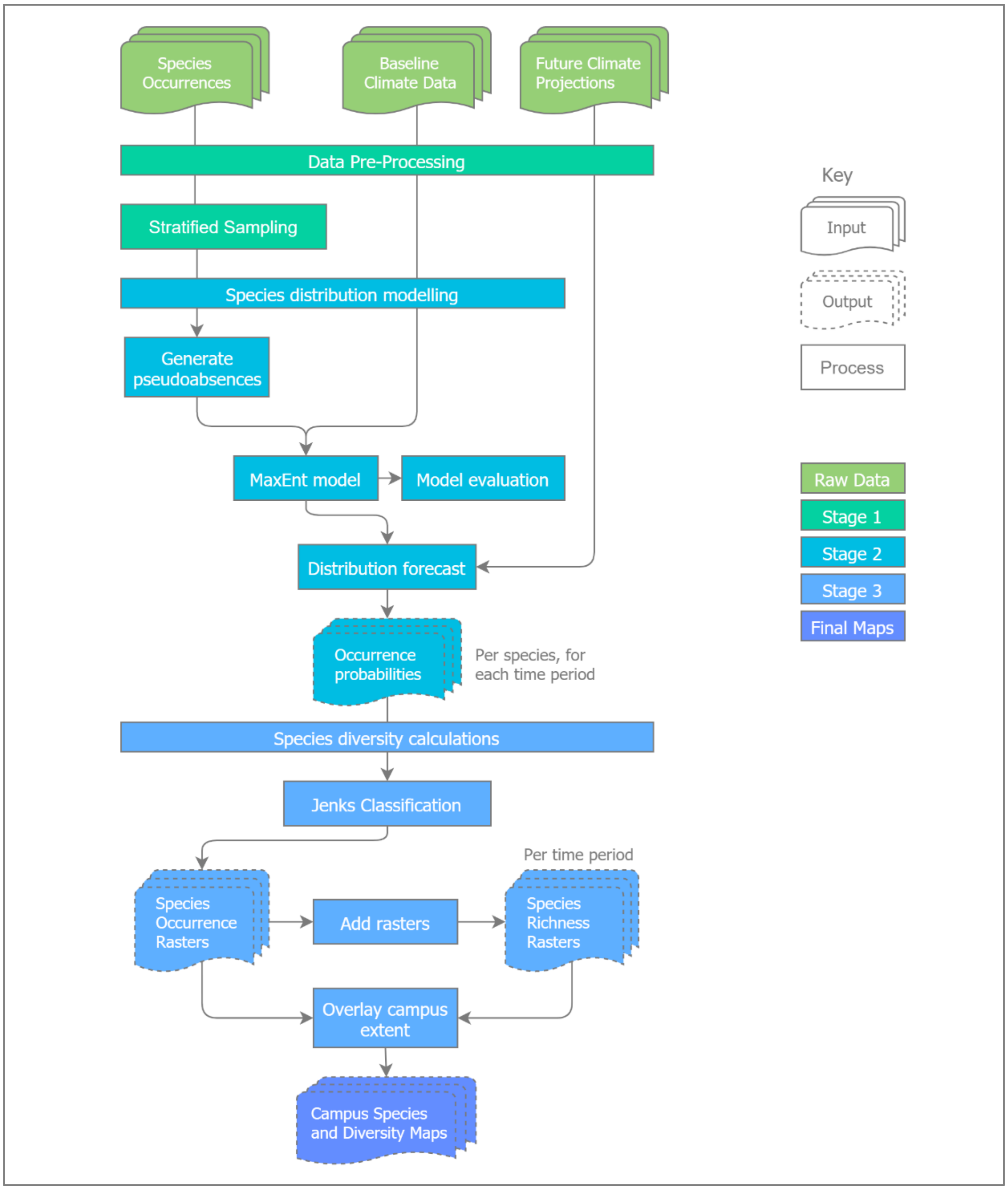

Figure 2. Process overview from 1) data acquisition and pre-processing, 2) species distribution modelling and evaluation to 3) species diversity calculations. The input data include species occurrences for 128

species, baseline climate data (1961-1990) and projected climate data (2050, 2080) for average annual temperature and precipitation. The final outputs are the species occurrence and diversity maps across North America, as well as the tree species and richness on campus for each of the three time periods.

3.2 *Data pre-processing*

A cartographic model was built using ArcGIS to automate pre-processing for each of the species datasets. The model iterated through all csv files containing species occurrence data and converted the tabular coordinates into points. Invalid points such as those occurring in water, and entries with duplicate geometries were removed. Then, the model projected the datasets from WGS 1984 to the Canadian Lambert Conic Conformal Projection to match the reference system of the climate data. Using this projection, distances across the area of interest are preserved in order to sample accurately stratified points for each species. All species and climatic datasets were imported into R for further processing. To improve model accuracy, a presence point was added to each dataset at the location of the UBC Vancouver Campus (49.2606° N, 123.2460° W) if missing from the data. To reduce geographic biases caused by higher rates of sampling in urban areas, each point occurrence dataset was subset by stratified sampling to retain one random point from each 10 km^2 cell (Veloz, 2009). The result is one feature dataset per species with no more than one point per 10 km^2 area. Species datasets with less than 50 points remaining were removed from the analysis to ensure sufficient data for model accuracy (Stockwell & Peterson, 2002). Of 180 original species, 128 were retained for distribution modelling. The climate rasters were aggregated to 10 km resolution to reduce computation time for all model runs and to match the species observation data.

3.3 *Species distribution modelling*

One of the mostly widely used tools for species distribution modelling is MaxEnt, a machine learning software which models suitable species habitat from a set of environmental predictors (Phillips et al., 2006). MaxEnt generates logistic predictions of species habitat by calculating a distribution of maximum entropy (i.e., the greatest spread for a set of climatic constraints). MaxEnt is advantageous for its high predictive accuracy compared to other models, and because it uses available species presence data. However, it requires the generation of pseudoabsences to be effective—assumed absence records that define the range of uninhabited climatic conditions (Elith et al., 2006). Since the species datasets are fairly large with hundreds to thousands of points each, 1000 pseudoabsences were selected using the ‘SRE’ method (Barbet-Massin et al., 2012). The technique creates a ‘surface range envelope’ which contains 95% of the presence points, and selects random pseudoabsences outside of the range. MaxEnt also assumes that environmental predictors are uncorrelated, hence the models are susceptible to overfitting (Merow et al., 2013). To address this issue, the predictors were limited to average annual temperature and average annual precipitation, two significant climate variables for tree survival (Fisher et al., 2018). Presence and pseudoabsence data were weighted equally (Thuiller et al., 2009) and all other default parameters were kept for generating the species ranges.

3.4 *Validation and model evaluation*

For cross-validation of models, a random subset of 75% of the data was used for modelling while the other 25% was used to evaluate predictive performance. The data-split was replicated ten times per species to reduce spatial autocorrelation effects (Briscoe et al., 2014). To assess the accuracy of the models, a confusion matrix was created with sensitivity (fraction of true positives) to quantify omission error, and specificity (fraction of true negatives) to quantify commission error. The true skill statistic (TSS), a normalized measure of overall accuracy calculated as sensitivity + specificity – 1 was obtained; it ranges from -1 to +1, with values below zero being no better than random assignment (Allouche et al., 2006). The AUC value or area under the receiver operating characteristic (ROC) curve was also reported; this is the probability that a random site of occurrence is more likely to be inhabited than a random absence site, and is often used to indicate overall model performance (Elith et al., 2006). The value may range from 0.5-0.69, poor performance; 0.7-0.79, reasonable; and 0.8-1.0, excellent performance (Liu et al., 2005). To optimize accuracy of forecasts, an ensemble model for each species was computed as the mean of all replicate models with acceptable performance (ROC > 0.7) and used to project species distributions into the 2050 and 2080 scenarios (Araújo & New, 2007).

3.5 *Quantifying range shift and diversity*

The outputs of MaxEnt are rasters for each species distribution in 2050 and 2080, where the cell values represent the probability of occurrence from 0 to 1. To classify the probabilities as either species presence (1) or absence (0), the Natural Break (Jenks) Classification system was used to determine a threshold above which the species is assumed to be present. This classification method clusters similar values into the two groups and maximizes the differences between presence and absence cells (Lim et al., 2018). To obtain a measure of range shift, the rasters were converted to polygons and centroid coordinates were extracted as the average range latitude. The shift in average range latitude for each climate scenario was compared for broadleaf and coniferous groups using a two-way Anova test. The test informs the significance of differences between tree type, significance of differences across time, and whether climate factors have a significantly different impact depending on tree type.

For each date range (baseline, 2050 and 2080) the binary rasters representing each species distribution was summed to obtain species richness maps (Tobeña et al., 2016). The presence of each species, as well as overall species richness on the UBC campus at the different time periods was extracted by overlaying the rasters with the study area (Burton & Wiersma, 2016). To examine predicted change in species richness at the continental scale, species richness in the baseline year was subtracted from species richness in 2080.

4. Results

4.1 *Projected range shifts*

MaxEnt climate-based projections for 2050 and 2080 were created for 128 campus tree species, for a total of 256 future species distributions across North America. All species ranges observed a northward shift from the baseline year to 2050 as well as from 2050 to 2080 according to average range latitude. On average, campus tree species ranges are projected to shift northwards by 8.1º (~ 900 km) in the coming century from 40.7º N to 48.7º N. Most of the expected northward range displacement occurs in the next few decades, with a 5.0º increase for 2050 and an additional 3.1º increase from 2050 to 2080.

Figure 3 displays the change in average range latitude across the study period for broadleaf and coniferous species, demonstrating that the impact of climatic shift on suitable habitat is slightly higher for the broadleaf trees (+8.18º) relative to conifers (+7.88º). There is greater variability in the current and future ranges of conifer species on campus; the coniferous species are also more suited towards northern latitudes than the broadleaf species based on their higher average range latitudes ($p < 0.001$). This observation persists through time as climates favourable for each species type are projected to expand northwards at similar rates; there is no significant difference between the effect of climate change on average range latitude of broadleaf and coniferous species ($p = 0.971$).

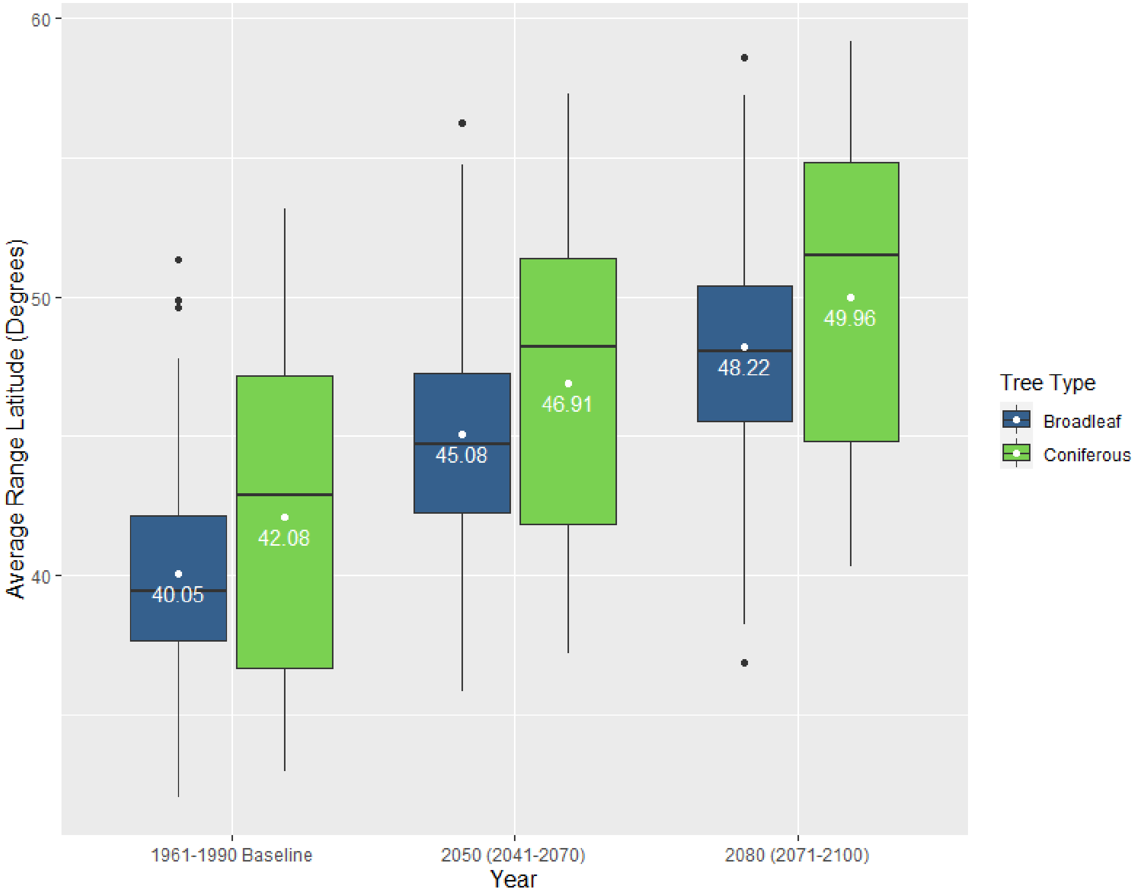

Figure 3. The average latitude of campus tree species ranges increases over time from the baseline year to 2080, representing a northward shift of ~8.2º for broadleaf species, ~7.9º for coniferous species, and ~8.1º across all species for the worst-case emissions climate scenario (RCP 8.5). The average latitude is denoted in white for each year and subgroup.

4.2 *Projected species diversity*

The species richness of trees that have suitable habitat on campus is projected to decline from the baseline year to 2050 and 2050 to 2080, starting from a maximum of 128 species in the baseline dataset (Figure 4). Due to limitations of model accuracy, 4 of 128 species distribution models indicated that the UBC Vancouver campus was not considered suitable habitat in the baseline year, and are excluded from further calculations of species richness. In total, projections indicate that 40 of 124 (32%) tree species will lose their suitable habitat on campus at the end of the century. Examining the contribution from different tree types, 23 of 88 (26%) broadleaf species and 17 of 36 (47%) coniferous species will lose their suitable habitat. There is increased broadleaf presence in the remaining 84 species; the composition shifts from 71% broadleaf, 29% coniferous to 77% broadleaf, 23% coniferous in 2080.

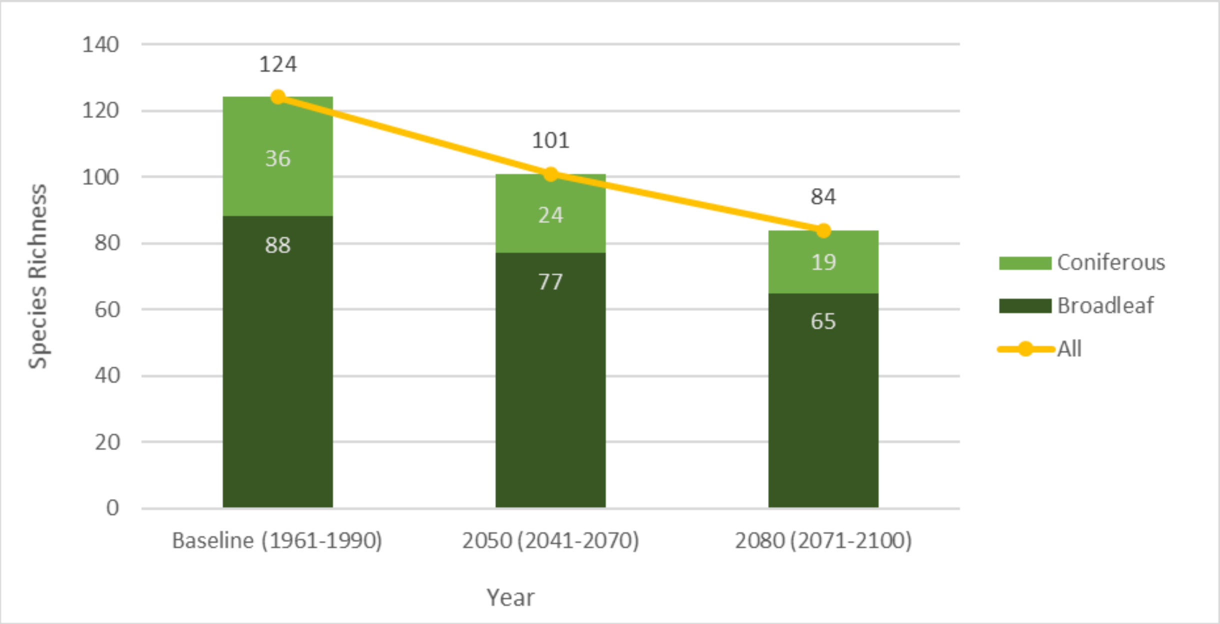

Figure 4. There is a projected decrease in species richness and change in composition by tree type from the baseline year to 2080 on the UBC Vancouver campus. 65 of 88 (74%) broadleaf species and 19 of 36 (53%) coniferous species are expected to retain their suitable climatic conditions on the UBC Vancouver campus at the end of the century.

Considering the larger context of North America (Figure 5), there is a projected increase in species richness at northern latitudes above 45º N and along the western Rocky Mountain range for trees found on the UBC Vancouver campus. As species ranges shift northward, fewer retain their suitable habitat at lower latitudes; there is a projected decrease below ~43º N and along the west coast including the UBC campus region.

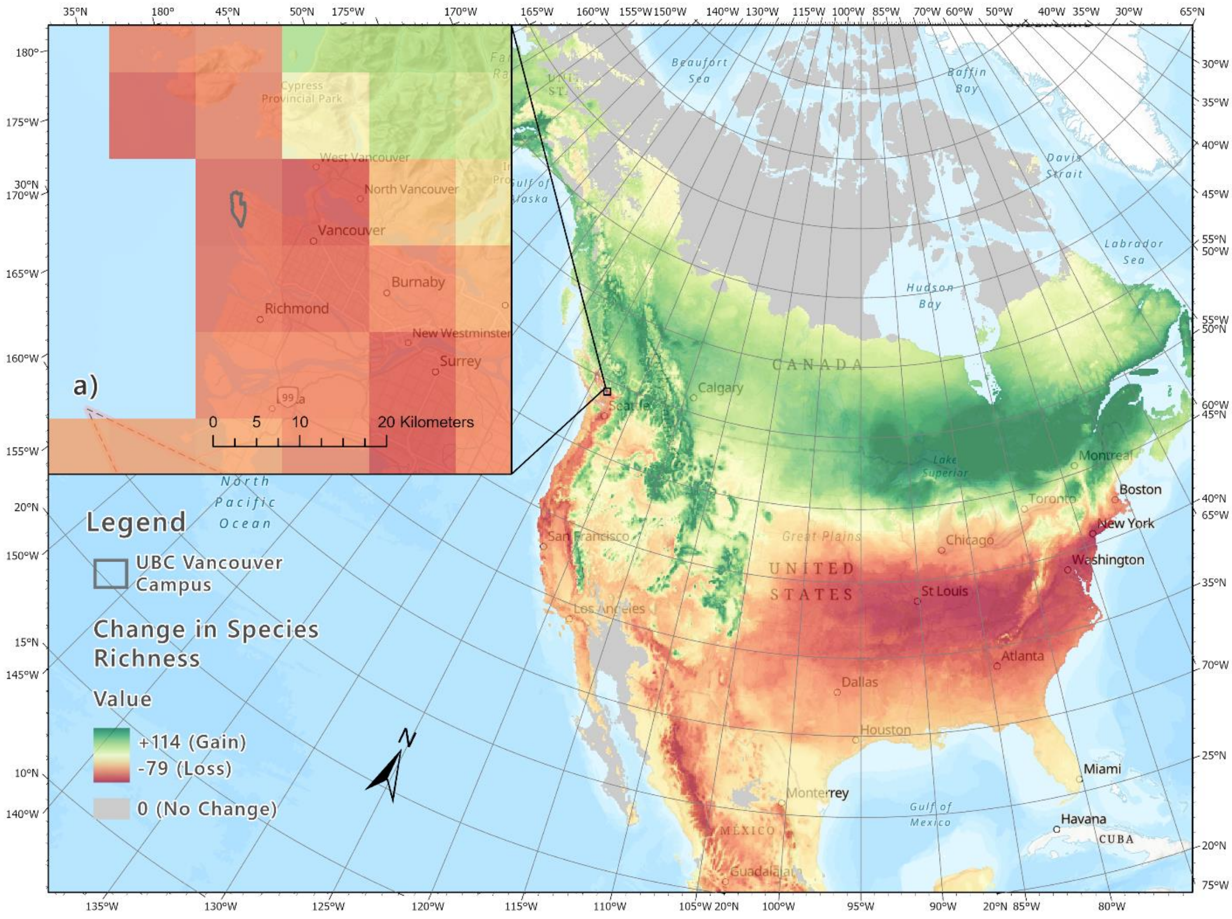

Figure 5. Projected change in species richness of UBC campus trees across North America according to climatic suitability. Campus species are projected to gain suitable habitat above 45º N across North America, and lose habitat below 43º N as well as on the west coast. Panel a) shows that the UBC Vancouver campus may face a decrease of 40 species with suitable habitat from the baseline year 1990 to 2080. Base imagery are referenced to the WGS 84 Lambert Conformal Conic Projection and sourced from ESRI, OpenStreetMap contributors and the GIS User Community (2021).

4.3 *Validation and model performance*

The predictive performance of all species distribution models were moderate to excellent with variation across taxa (Table 1), where the true skill statistic (TSS) > 0.5 and area under the receiver operating characteristic curve (AUC) > 0.7 are the thresholds for acceptable model performance. Final ensemble models, which were the average of individual models with AUC scores over 0.7 performed better than individual models as expected (TSS score of 0.921 vs. 0.905; AUC score of 0.980 vs. 0.969), and were used to project species ranges into 2050 and 2080 climate scenarios.

For individual species models, the minimum TSS and AUC scores were 0.676 and 0.838, respectively. Species with TSS scores below 0.8 and AUC scores below 0.9 performed acceptably despite lower accuracy scores, including bristlecone fir (*A. bracteata*), Amur maple

(*A. japonicum*), Chinese fir (*C. lanceolata*), and oriental cherry (*P. serrulata*). These species had few presence points in their modelling dataset (105, 59, 138, and 85 respectively) compared to species with thousands of records, potentially impacting the accuracy of the models. Average sensitivity (93.5) and specificity (98.0) indicate that false negatives were more common than false positives. One species, the deodar cedar (*C. deodara*) had a specificity score of 0, indicating that all predictions resulted in false positives. However, the species had few (< 25) observations set aside for evaluation following the 75/25 data split. Overall, models for broadleaf species performed slightly better than models for coniferous species across all accuracy metrics except for sensitivity.

Table 1. Summary of model evaluation results and confusion matrix scores for campus tree species, including the true skill statistic (TSS), area under the receiver operating characteristic curve (AUC), sensitivity (true positive) and specificity (true negative). Model performance was acceptable for all species and is on average high across accuracy metrics (> 0.9).

Evaluation Metric	**Broadleaf**	**Coniferous**	**All**	**Evaluation Metric**	**Broadleaf**	**Coniferous**	**All**
TSS (-1 to 1)				**Ensemble TSS (-1 to 1)**			
Minimum	0.779	0.676	0.676	Minimum	0.828	0.817	0.817
Maximum	0.979	0.937	0.979	Maximum	0.965	0.950	0.965
Mean	0.910	0.896	**0.905**	Mean	0.922	0.919	**0.921**
AUC (0.5 to 1)				**Ensemble AUC (0.5 to 1)**			
Minimum	0.890	0.838	0.838	Minimum	0.911	0.923	0.911
Maximum	0.990	0.987	0.990	Maximum	0.996	0.995	0.996
Mean	0.971	0.962	**0.969**	Mean	0.981	0.977	**0.980**
Sensitivity (0 to 1)				**Specificity (0 to 1)**			
Minimum	82.8	85.2	82.8	Minimum	87.0	0.00	0.00
Maximum	100	100	100	Maximum	100	100	100
Mean	93.4	93.5	**93.5**	Mean	98.8	96.3	**98.0**

5. Discussion

5.1 *Overview*

To investigate potential climate-induced shifts of arboreal composition and diversity on the UBC Vancouver campus, this study used species distribution modelling to predict habitat suitability for 128 campus tree species in 2050 and 2080. It was hypothesized that: (1) campus species would observe a northward shift in their predicted ranges following the displacement of their suitable climatic habitat, and (2) the UBC campus should expect tree diversity loss in the coming century as climatic shifts exceed local tolerances of vulnerable species, such as species adapted to higher latitudes and native conifers. Overall, the results support both predictions and provide further insight based on the impact faced by individual species.

5.2 *Northward species range shifts*

Predicted species distributions for 2050 and 2080 indicate that a majority of campus tree species are likely to face pressure to migrate northwards under future conditions. The average range shift of 8.1º (~ 900 km) north suggests that climate change will have a substantial impact on the suitable habitat for trees at UBC Vancouver. The impacts are not only apparent for the set of campus species as a whole, but individually as most displacements range from 611-1189 km. Shifts are expected to have most impact from now to 2050, presenting concern for species with limited tolerance to rapid environmental change. Findings are concurrent with those across North America and indicate increased severity of climate-induced shifts in recent years. For example, McKenney et al. (2007) predicted an average northward shift of 700 km for 130 North American tree species in 2080. Hamann and Wang (2006) also found that tree species with their northern range limit in British Columbia are expected to expand northward by at least 100 km per decade.

5.3 *Diversity loss and compositional change*

Over a third of the campus tree species are vulnerable to climatic habitat loss on the UBC campus, presenting a threat to future species diversity. Although results suggest that climate change impacts coniferous and broadleaf trees with similar severity, the coniferous species occur at higher latitudes and have greater variation in their preferred habitats; this may indicate that their habitat requirements are more specialized, increasing their vulnerability to climate shift at the local scale. These results partially agree with Hamman and Wang (2006), which found that conifer species of British Columbia are expected to lose a large portion of their suitable habitat, but common broadleaf trees will be generally unaffected. However, their climate scenarios were based on the previous IPCC Third Assessment Report (2001) and modelled shifts in ecosystems only; this study considered recent emission forecasts and examined the impact on individual species. In a broader scale context, the west coast of North America faces greater potential decline of species richness than areas of similar latitude, likely due to the increased threat of heat and drought conditions for trees suited to mild and moist climates (Aubin et al., 2018; Daniels et al., 2011).

5.4 *Model performance and limitations*

Overall, the MaxEnt species distribution models performed well and demonstrate that climate-based forecasting can be used to reliably predict future habitat suitability of tree species. As expected, the ensemble models incorporated variation between individual runs to reduce uncertainty and improve predictions. Despite accurate performance of models, several limitations of this study are important to consider. First, climate-based species distribution models do not consider the actual migration capacity of tree species and are only a proxy for species richness. Aside from climate, physiological factors like reproduction method, cold hardiness and drought tolerance may also impact the vulnerability of species and actual range shifts in the future (Aubin et al., 2018). Secondly, the results are limited to the set of 128 taxa with sufficient data and do not represent all species on the UBC campus. Rather than an exact change in species richness, findings are relevant to the dominant species that would have a noticeable impact on diversity.

Furthermore, model quality reflects data quality and incomplete datasets can underestimate the true range of suitable habitat conditions. Similar to the bioclimatic habitat study conducted by Gray and Hamann (2013), false negatives were more common than false positives, indicating that the tree species presences are more easily underestimated at the local scale; trees past the seedling stage may be able to withstand a wider range of conditions than initially thought. The study also limits climate predictors to mean annual temperature and mean annual precipitation to prevent multicollinearity issues, even though many monthly and seasonal temperature and precipitation variables are also available. The models could vary if variables such as drought indices or soil moisture were included, however these variables were not included in the ClimateNA dataset and are not readily available as future projections across North America, especially at higher latitudes (Quiring et al., 2015). Lack of observed soil moisture data makes long-term prediction and validation difficult, and accurate predictions of drought indices depend on soil moisture, soil content and land surface simulations. Furthermore, soil moisture data aggregated to the 10 km resolution of this study would disregard site-specific conditions affecting tree habitat suitability, such as soil depth, content and porosity (Houle et al., 2012). Lastly, different relationships between climate variables and species occurrence may exist at multiple scales and localities; for the purposes of this study, the widespread climatic niche of each species is sufficient to make conservation-based conclusions.

5.5 *Future directions and implications*

To fully answer the question of how arboreal composition will change in the future, additional studies will need to be conducted on the adaptation response of individual species, as well as to determine the potential for increased diversity. This study focuses on the possible decline of species that already exist on campus, however species from southern latitudes may also expand their ranges into the UBC region in response to climate shifts. Horticultural species may also be brought into campus through assisted migration or translocation. Future studies may investigate the biological traits of trees to predict their actual migration capacity in the future, expand beyond the broadleaf vs. coniferous distinction to examine impacts on native vs. exotic trees, or determine rapid vs. slow dispersal ability to identify ideal planting species.

This study has important implications at UBC Vancouver, with possible applications in both landscape and ecosystem service planning. Campus trees that are likely to retain their suitable habitat are favourable for tree planting initiatives and diversity enhancements included in the upcoming Climate Action Plan 2030, which may include carbon sequestration strategies to offset carbon emissions (UBC, 2021). For example, northern red oak (*Q. rubra*), a species commonly cultivated in parks and gardens was projected to have the least range shift of 1.3º north. With interest in highly impacted taxa, detailed case studies can be conducted on individual tree species to assess their potential to survive on campus as part of protection strategies. One of such species could be silver birch (*B. pendula*), which had the greatest projected range shift of 17.8º north; it is an ornamental tree adapted to northern European latitudes. With further examination, the list of species at risk provide insight on which ecosystem services may need to be replenished or carefully maintained in the future. For instance, coniferous trees provide carbon sequestration services year-round while broadleaf trees can provide shading and aesthetic value (Clapp, 2014).

Depending on availability of a complete campus tree inventory, determining the locations of species on campus and number of individuals can be used to map fine-scale change over the decades. Vulnerability of neighbourhoods to ecosystem service loss can be determined based on the presence of trees subject to severe climate-induced habitat shifts; this may inform plans to restore specific ecological functions of these species such as air quality, temperature and surface water regulation (Bodnaruk et al., 2017; Demuzere et al., 2014). Overall, this study highlights the urgency of climate-induced habitat decline at UBC Vancouver and provides early insight for a ‘Trees and Biodiversity’ strategy to maintain tree diversity at the local scale.

At the regional scale, ongoing research on tree species’ climatic tolerances are also being conducted to assess the potential for assisted migration and reforestation. For example, the Assisted Migration Adaptation Trial in British Columbia is an effort to select tree species best adapted to current and future climates to retain arboreal diversity across the province (Government of British Columbia, 2016). With knowledge on species-specific adaptation capacity, assisted translocation strategies can be complemented by climatic range models to determine the species most likely to survive in target tree planting locations (Aitken and Bemmels, 2015). By identifying species that are most and least exposed to climatic shift, this study demonstrates that climate-based species distribution modelling can be an effective way to inform future forest management plans. In the face of global climate change, it is essential to manage arboreal diversity to mitigate the negative consequences of rapid warming in urban communities.

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Appendix: Project Archiving

Project Dataset

This research was conducted from September 2018 to April 2021 for Campus & Community Planning, University of British Columbia (https://planning.ubc.ca) as a SEEDS applied research project. The project dataset is archived and publicly accessible on the Masters of Geomatics for Environmental Management (MGEM) Scholars Portal Dataverse, available for download at https://doi.org/10.5683/SP2/3RTCYF.

The dataset contains:

- Predicted habitat ranges for 128 UBC campus tree species across North America for three time periods: baseline (1961-1990), 2050s (2041-2070) and 2080s (2071-2100). All species ranges for a given time period are contained in the same polygon shapefile.

- Predicted tree species diversity across North America for three time periods: baseline (1961-1990), 2050s (2041-2070) and 2080s (2071-2100). These are 10-km resolution raster surfaces containing values for species richness across the study area.

- Tabular dataset containing tree species of interest, taxonomic classifications, descriptive attributes, model performance metrics, average range latitude, and difference in average range latitude for each species range per time period.

- R, Python processing scripts and ArcGIS cartographic models for conducting the modelling analysis, statistical tests and generating result figures shown in this report.

For further technical details, please review the *readme.txt* file included in this project's dataset on the MGEM Dataverse.

StoryMap

The ArcGIS StoryMap 'UBC Trees in a Changing Climate' was created to accompany this report and can be found at the following link:
https://storymaps.arcgis.com/stories/bac335cc3f93415288920c950bb05f27

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