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Research Note

Using climate analogues and vulnerability metrics to inform urban tree species selection in a changing climate: The case for Canadian cities

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HIGHLIGHTS

- Climate analogues and vulnerability metrics can be used to inform species selection.
- Across 10 Canadian cities, 233 species (~67 %) will be at high risk of increased temperatures by 2050.
- Resilient species represent potential alternatives to replace species at high risk of climate change in Canadian cities.
- Our approach is a potential tool to aid urban tree selection and integrate climate change into urban forest management.

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ABSTRACT

Urban forests provide ecosystem services to more than 4.2 billion people living in cities; however, the provision of these services is threatened by climate change. Cities will experience novel, warmer climates that will impact tree species survival. Here, we present an empirical approach combining the use of climate analogues and vulnerability metrics to guide urban tree species selection. Climate analogues can be used to identify where the current climate in a given location is similar to the projected future climate of another location. Using vulnerability metrics, tree species in both locations can then be compared and species at risk of future climate change can be identified and substituted with species known to be resilient to climatic changes in the other location. Using Canadian cities as a case study, we show how our approach can become a useful tool to inform species selection and facilitate urban forest decision-making in response to climate change.

1. Introduction

Urban forests provide ecosystem services that benefit more than 4.2 billion people living in urban areas worldwide (Liu, He, Zhou, & Wu, 2014). However, to provide these services sustainably, urban forests need to perform well and survive into the future. Climate change, therefore, represents a threat to the persistence of urban forests, likely leading to increased tree mortality (Esperon-Rodriguez et al., 2022a; Ordóñez & Duinker, 2015; Savi, Bertuzzi, Branca, Tretiach, & Nardini, 2015). Thus, urban forest stability may depend on the identification of well-adapted tree species to both current and future climates (Esperon-Rodriguez, Tjoelker, Lenoir, Baumgartner, Beaumont, Nipperess, Power, Richard, Rymer, & Gallagher, 2022b; McPherson, Berry, & van Doorn, 2018; Way & Oren, 2010).

As temperatures increase, there will be spatial shifts in climate zones, modifying boundaries of existing zones (Williams, Jackson, & Kutzbach, 2007). Cities will experience novel, more extreme climates that may jeopardize tree growth and survival (Fahey, Bialecki, & Carter, 2013; Yan & Yang, 2018). To build climate-resilient urban forests, it is necessary to understand shifts in climate zones and how they will impact

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urban forests. This can be achieved by assessing species' climatic tolerance.

Climatic tolerance varies among tree species depending on their origin (e.g., warm *vs* temperate climates) and their trait plasticity (Esperon-Rodriguez et al., 2020; Hanley, Arndt, Livesley, & Szota, 2021); therefore, it can be used to guide species selection (Hirons et al., 2021; McPherson et al., 2018; Sjöman, Hirons, & Bassuk, 2018). Unfortunately, robust data are not readily available for many species. As an alternative, the species climatic safety margin (hereafter safety margin) can be used to estimate the vulnerability of a species to climate change. This metric describes the intrinsic species sensitivity to climate change and indicates potential tolerance to changing climate conditions in natural and urban ecosystems (Clusella-Trullas, Garcia, Terblanche, & Hoffmann, 2021; Esperon-Rodriguez et al., 2022b; Foden et al., 2019; Gallagher, Allen, & Wright, 2019; Kitudom et al., 2022).

Safety margins, in combination with climate analogues, can be used to guide species selection in cities. Climate analogues can help identify where the current climate in a location is similar (i.e., analogous) to the projected future climate of another area. This results in pairs of different geographical locations sharing similar climates for different time periods (Rohat, Goyette, & Flacke, 2018). This approach has been used as an index of climate risk, to assess the velocity of climate change, and for biodiversity conservation by locating climate refugia (e.g., Beaumont, Esperon-Rodriguez, Nipperess, Wauchope-Drumm, & Baumgartner, 2019; Beniston, 2014; Ohlemüller, Gritti, Sykes, & Thomas, 2006). In cities, climate analogues have been used to evaluate the economic impact of climate change and to characterize climatic shifts (Bastin et al., 2019; e.g. Hallegatte, Hourcade, & Ambrosi, 2007; Rohat et al., 2018); recently, they have been utilized for urban tree species selection (Itani, Al Zein, Nasralla, & Talhouk, 2020; Watkins, Cameron, Sjöman, & Hitchmough, 2020).

In this research note, we evaluated the potential of using climate analogues and safety margins to inform species selection considering future climate change. We chose the safety margin as a measure of how much warmer (or drier) a city could become before the climate tolerance of its resident species is exceeded. We used Canadian cities as a focal point in the analysis while integrating other non-Canadian, regional, and world cities for comparison and illustration. That is, species identified as being able to grow in a safe baseline climate (i.e., within the species realized climatic tolerance) in non-Canadian cities can replace species that are predicted to be at risk of future climate change in Canadian cities.

Canadian cities provide a good case study because temperature increases are predicted to be higher in North American cities compared to cities at lower latitudes (Esperon-Rodriguez et al., 2022b). Further, recent heatwave events in summer 2021 highlighted the risk of Canadian cities and their city dwellers to climate extremes (Philip et al., 2021). Many Canadian cities view the urban forest as a key urban infrastructure that supports urban liveability and wellbeing (Almas & Conway, 2016), yet integrating climate change adaptation and resilience into urban forest management remains limited (Ordóñez & Duinker, 2015; Steenberg, Duinker, & Nitoslawski, 2019). Therefore, demonstrating the use of climate analogues is an opportunity to show more concretely what climate change means for Canadian urban forests, and to indicate the potential of this tool to enhance urban forest management and decision-making.

2. Methods

2.1. Climate data

Baseline and future climate data were obtained from CHELSA Version 1.2 (Karger et al., 2017) at ~1 km spatial resolution. This resolution, however, can be limited to identifying microscale areas where harsh conditions can be exacerbated due to the urban heat island effect, or areas where conditions are more benign due to the vegetation effect on the microclimate (e.g., high canopy cover) or presence of wind (Alavipanah, Wegmann, Qureshi, Weng, & Koellner, 2015; Corburn, 2009; Kidder & Essenwanger, 1995). We selected five climate variables known to affect species distributions and increase urban tree mortality (O'Donnell & Ignizio, 2012; Yan & Yang, 2018): (1) mean annual temperature (MAT); (2) maximum temperature of the warmest month (MTWM); (3) minimum temperature of the coldest month (MTCM); (4) annual precipitation (AP); and (5) precipitation of the driest quarter (PDQ). Then, we estimated the threshold of the 95th percentile of MAT and MTWM and the 5th percentile of MTCM, AP and PDQ to assess the extremes of these variables as indicative of climatic tolerance (i.e., species' thermal and drought stress tolerance for survival and growth).

Climate data were projected to the Mollweide projection, an equal area pseudocylindrical map projection (ESRI:54009). Baseline climate represents the average climate conditions from 1979 to 2013. For future climate data, we used projections for 10 General Circulation Models (GCMs) (Table S1). We extracted values of the five aforementioned climate variables for each GCM and estimated the median across all 10 GCMs for our analyses. Here, we present results for the time period 2050 (average for 2041–2060) and the Representative Concentration Pathways (RCP) 6.0, which project a peak in emissions around 2080 followed by a decline (Meinshausen et al., 2011). Importantly, using a different set of GCMs or RCPs might affect the estimations of climate change projections and the vulnerability assessment developed for cities and species.

2.2. Urban areas, species composition and vulnerability metrics

Polygons defining the boundaries of 77 cities in 20 countries from Europe and North America were obtained from Kelso and Patterson (2012) as a shapefile (WGS84; 1:10 million; EPSG:4326). Data were projected to the Mollweide projection (ESRI:54009). Species composition for each city was obtained from the Global Urban Tree Inventory database (Ossola et al., 2020). This database compiles presence data of 4,734 tree and shrub species found in 473 urban areas globally. Abundance data were not available for this database; therefore, our approach gives equal weight of vulnerability to all species.

Safety margin (S) was used as a vulnerability metric and was estimated for baseline (S_{Baseline}) and future (2050, RCP6.0; S_{Future}) climate conditions as the difference between a species' climatic tolerance ($Species_{\mathrm{ClimateVariable[i]}}$) and the climatic conditions experienced in the focal city ($City_{\mathrm{Climate}}$) as follows:

$$S_{Baseline} = \begin{cases} Species_{ClimateVariable[i]} - City_{BaselineClimate} (MAT, MTWM) \\ City_{BaselineClimate} - Species_{ClimateVariable[i]} (MTCM, AP, PDQ) \end{cases}$$

and

$$S_{Future} = \begin{cases} Species_{ClimateVariable[i]} - City_{FutureClimate} (MAT, MTWM) \\ City_{FutureClimate} - Species_{ClimateVariable[i]} (MTCM, AP, PDQ) \end{cases}$$

For S, the climatic tolerance of a species ($\mathrm{Species}_{\mathrm{ClimateVariable}[i]}$) was measured as the 95th (MAT, MTWM) and the 5th (MTCM, AP, PDQ) percentiles of the species' climate niche based on its global occurrence records for baseline climate. The city's climate ($City_{\mathrm{Climate}}$) was also estimated using the 95th and 5th percentiles for both baseline and future climates. A positive safety margin (S greater than 0) indicates that the climatic tolerance of the species exceeds climatic conditions in the focal city (e.g., cooler/wetter and thus safer); whereas a negative value ($S < 0$) indicates that the species is experiencing now or in the future "unsafe" climatic conditions exceeding its climatic tolerance (Esperon-Rodriguez et al., 2022b).

We highlight that species realized climatic niches are not equal to their fundamental niche. Species distribution data are incomplete, potentially leading to underestimations of the actual realized niche. Therefore, safety margins represent an approximation of their tolerances.

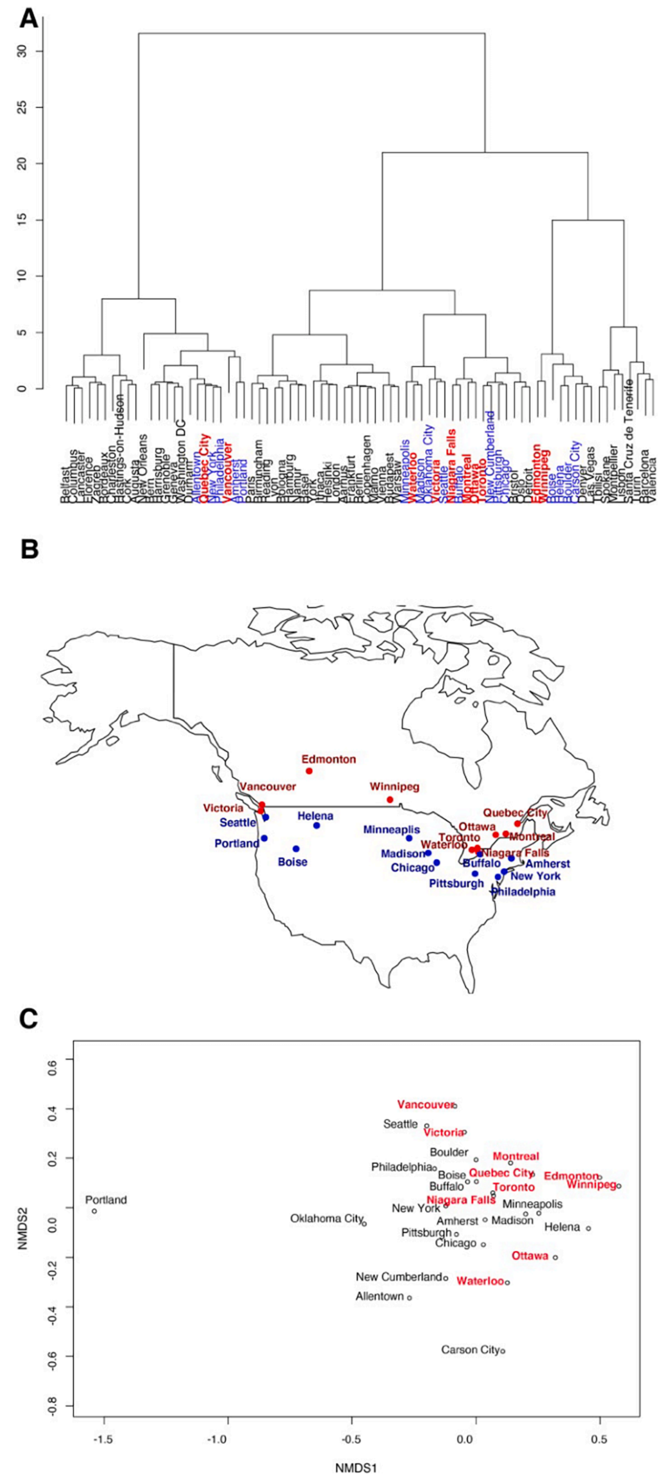

Fig. 1. Cluster analysis results for 77 cities to group cities with climate analogues based on three climate variables: (1) minimum temperature of the coldest month; (2) annual precipitation; and (3) precipitation of the driest quarter. Ten Canadian cities are indicated in red and cities in blue indicate the highest similarity in climate; these cities were used to evaluate species composition (**A**); geographic locations of cities in Canada and the US with climate analogues (**B**); and non-metric multidimensional scaling (NMDS) plot with results for the ordination of urban forest composition for 27 cities with similar climates (i.e., climate analogues); 10 Canadian cities are indicated in red (**C**). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Number of species predicted to exceed their mean annual temperature (MAT) safety margin by 2050 (RCP 6.0) in 10 Canadian cities and number of species predicted to have safety margins greater than their baseline MAT (“safe”); numbers in brackets indicate the number of species under safe conditions that are not present in Canadian cities and represent safe choices for planting in both the baseline and predicted future climate conditions of the Canadian cities. Each row indicates a pair of Canadian and US cities based on climate analogues and species composition. For detailed information on species see **Tables S3-S4**.

Canadian City	Unsafe species (2050)	US city	Safe species (baseline)
Edmonton	6	Helena	58 (58)
Montreal	81	Buffalo	130 (103)
Niagara Falls	92	Buffalo	130 (80)
Ottawa	33	Chicago	63 (63)
Quebec	35	Philadelphia	70 (70)
Toronto	92	Pittsburgh	50 (36)
Vancouver	175	Philadelphia	70 (68)
Victoria	119	Seattle	76 (56)
Waterloo	35	Madison	69 (46)
Winnipeg	7	Helena	58 (58)

2.3. *Statistical analyses*

Correlations among climate variables were evaluated using a Principal Component Analysis and based on the magnitude and direction of vectors, we selected MTCM, AP and PDQ to perform subsequent analyses (Fig. S1). We used Ward’s hierarchical clustering to identify climate analogues between baseline climates of non-Canadian cities ($n = 67$) and future climates of Canadian cities ($n = 10$). Ward’s method reduces the increase in the total within-cluster sum of squared error, which is proportional to the squared Euclidean distance between cluster centres (Murtagh & Legendre, 2011). We measured dissimilarity using Euclidian distances (Bouguettaya, Yu, Liu, Zhou, & Song, 2015; Walther, Lüdeke, & Gudipudi, 2019).

Once climate analogues were identified (i.e., clustered together) (Fig. 1A, B), similarities of species composition among cities were evaluated using non-metric multidimensional scaling (NMDS) based on a presence-absence matrix (Legendre & Legendre, 2012) (Fig. 1C). The distance between cities in the ordination space reflects dissimilarity in species composition —i.e., cities with similar scores are expected to have similar species composition. Based on climate analogues (i.e., cities clustered together) and species compositions (i.e., similar NMDS scores), we paired cities with the highest similarities by prioritizing cities with similar species compositions over climate analogues. Then, we identified species predicted to exceed their future safety margins in Canadian cities and species predicted to be safe under baseline climate in non-Canadian cities. These species represent potential alternatives to replace species at high risk of climate change in Canadian cities; new planting opportunities would aim to shift the species composition towards more resilient species.

All statistical analyses were performed using R version 4.0.5 (R Core Team, 2021). Specifically, we used the *vegan* package (Oksanen, Blanchet, Friendly, Kindt, Legendre, McGlinn, Minchin, O’Hara, Simpson, Solymos, Stevens, Szoecs, & Wagner, 2019) and the function *metaMDS*, without auto-transformation and Jaccard coefficient as the metric for the presence–absence community-by-site matrix.

3. Results

We identified 17 cities in the United States (US) today (baseline) as climate analogues for Canadian cities with a predicted climate of 2050 (Fig. 1B). Species composition varied among cities and did not necessarily reflect climate similarities or geographic location (Fig. 1C). Portland (US), for example, had similar climate to Vancouver, but its species composition was different compared to other cities (Fig. 1C). We paired Canadian cities with seven US cities based on climate analogues (i.e., cities clustered together) and species composition (i.e., similar

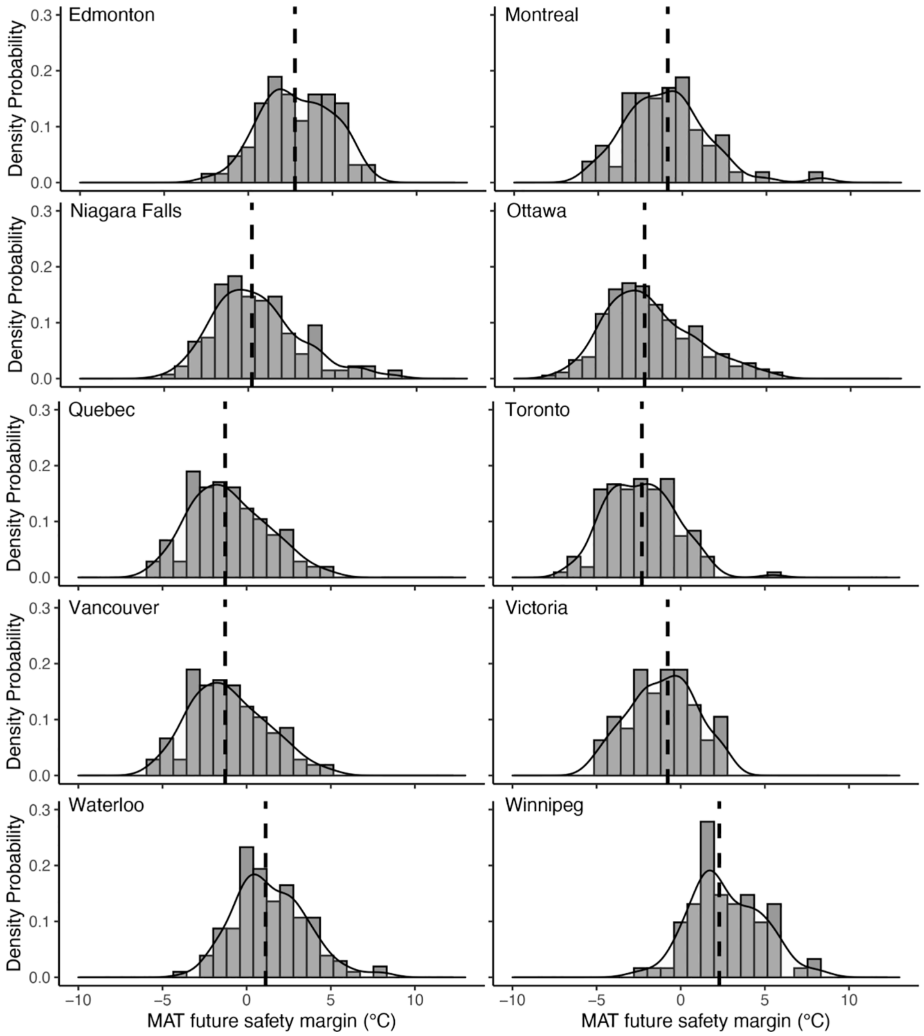

Fig. 2. Probability density of the 95th percentile of mean annual temperature (MAT) of future safety margins of each species across 10 Canadian cities. Black dotted lines indicate the median across species. A positive safety margin (S greater than 0) indicates species with a MAT climatic tolerance limit greater than that of future climatic conditions of each city; a negative value ($S < 0$) indicates species predicted to be under "unsafe" future climatic conditions. Data for 2050 and RPC 6.0. See **Supplemental Figs. S2-S5** for other climate variables.

NMDS scores) (Table 1).

Across 10 Canadian cities, 233 species (67 %) were predicted to exceed their MAT safety margin (i.e., climatic tolerance) by 2050 (See Table S2 for other climate variables). Of 37 families, the most vulnerable were Pinaceae, Rosaceae and Sapindaceae with 140, 83 and 80 species, respectively, exceeding their future MAT safety margin. The most vulnerable species were *Pinus banksiana* (the species exceeds its safety margin in nine cities where it is planted), *Acer tataricum* (eight cities), *Sorbus americana* (eight cities) and *Sorbus aucuparia* (eight cities) (Table S3).

Victoria (88 %; 119 species) and Vancouver (76 %; 175 species) had the highest proportion of species at risk of future climate change. In contrast, across seven US cities (i.e., analogue to future climate in Canadian cities), safety margins of 228 species (~74 %) were greater than that of baseline MAT and thus are safe (Table S4). For example, Victoria, which is predicted to have 119 species exceeding their safety margins by 2050, could incorporate up to 56 species currently in Seattle that are not presently planted in Victoria. These 56 species are safe species choices based on the baseline climate of Seattle and future climate of Victoria. Similarly, for Vancouver, 68 new species from Philadelphia could be incorporated into Vancouver's urban forest (Table 1). Despite the numbers of species exceeding their safety margins in Canadian cities, for most of the species, safety margins were narrow with median values of future safety margins of −0.4 °C for MAT, −1.2 °C for MTWM, −4.6 °C for MTCM, −48 mm for AP and −11.8 mm for PDQ (Fig. 2, S2-S5).

4. Discussion

The combination of climate analogues and safety margin data can advise urban tree species selection, integrate climate change into urban forest management, and facilitate urban forest decision-making in response to climate change. Our work develops from climate analogue evaluations carried out using currently available online platforms that visualize and analyze such analogues, including "Climate Analogues" (Copernicus Climate Change Service, https://climate.copernicus.eu>), "Climate Matching Tool" for Europe (<https://climatematch.org.uk>; Broadmeadow, Ray, & Samuel, 2005) and "Climate Change in Australia 2015" (<http://www.climatechangeinaustralia.gov.au/>; Clarke, Whetton, & Hennessy, 2011). These free, available platforms can be used to replicate our approach in different cities.

We do not suggest that the urban forests between climate analogues are equal or replaceable. Rather, we advocate that urban forest management decisions can integrate better information about the future climate of cities and urban tree species that will not grow as expected given these new conditions. This information can help make better decisions about urban tree species selection, including introducing new species and genotypes, accounting for the potential risk associated with such introductions (e.g., invasiveness, light regimes, pest and pathogens, biodiversity connections, social preferences; Almas & Conway, 2016; Brandt et al., 2016; Ordóñez & Duinker, 2015; Steenberg et al., 2019), protecting or safeguarding existing vulnerable tree species, and working alongside the nursery sector to evaluate which tree species to grow and potentially changing urban tree supply (Steenberg, Millward, Nowak, & Robinson, 2017), among other decisions.

Our approach can be used in combination with ecological functional approaches (Paquette et al., 2021) and trait-based analysis (Esperon-Rodriguez et al., 2020; Hirons et al., 2021; Watkins, Hirons, Sjöman, Cameron, & Hitchmough, 2021) to improve our understanding of urban forest performance. When available, integrating data on species physiological tolerance and trait plasticity can enhance the identification of species resilient to climate change (Esperon-Rodriguez et al., 2020; Hanley et al., 2021). Global and regional plant trait databases such as TRY, AusTraits for Australia, and BROT 2.0 for the Mediterranean Basin (Falster et al., 2021; Kattge et al., 2020; Tavşanoğlu & Pausas, 2018) can provide information on life history and physiological traits relevant to climatic tolerances. Importantly, this does not replace other considerations for tree species selection to maximize urban forest performance, such as integrating biotic risk factors and including abiotic factors of stress, such as soil quantity and quality, and windthrow (Hilbert, Roman, Koeser, Vogt, & Van Doorn, 2019; Jahani & Saffariha, 2022).

Given that in many Canadian cities only a few tree species are in high abundance, it may be important for some cities to account for the climate risk for rare species with low abundance, considering that the level of risk for these species may not be lower than the risk for the most abundant species. In Toronto, for example, the two most abundant tree species, *Acer negundo* and *Acer saccharum* (Bourne & Conway, 2014) were predicted to exceed their future safety margins, thus, highlighting the importance of considering biodiversity conservation when identifying the climate risk for rare species, with native rare and vulnerable species possibly warranting more attention.

Climate change threatens the persistence of Canadian urban forests, although its impacts will vary across cities. Given the importance of promoting urban tree longevity and recognizing that trees take decades to grow before providing substantial ecosystem services, it is recommended that urban forests be planned decades in advance. Ultimately, improving urban tree species selection can decrease economic losses, optimize the provision of key ecosystem services, and generally enhance the environmental and social benefits provided by urban forests.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104578.

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