Vulnerability of Street Trees in Upper Midwest Cities to Climate Change

Leslie A. Brandt[1]*, Gary R. Johnson[2], Eric A. North[2], Jack Faje[2] and Annamarie Rutledge[3]

[1] USDA Forest Service, Northern Research Station, Northern Institute of Applied Climate Science, St. Paul, MN, United States, [2] Department of Forest Resources, University of Minnesota, St. Paul, MN, United States, [3] Northern Institute of Applied Climate Science, Michigan Technological University, Houghton, MI, United State

Urban trees play an important role in helping cities adapt to climate change, but also are vulnerable to changes in climate themselves. We developed an approach for assessing vulnerability of urban tree species and cultivars commonly planted in cities in the United States Upper Midwest to current and projected climate change through the end of the 21st century. One hundred seventy-eight tree species were evaluated for their adaptive capacity to a suite of current and future-projected climate and urban stressors using a weighted scoring system based on an extensive literature review. These scores were then evaluated and adjusted by leading experts in arboriculture in the region. Each species or cultivar's USDA Hardiness Zone and American Horticultural Society Heat Zone tolerance was compared to current and future heat and hardiness zones for 14 municipalities across Michigan, Wisconsin, and Minnesota using statistically downscaled climate data. Species adaptive capacity and zone tolerance was combined to assign each species one of five vulnerability categories for each location. We determined the number of species and trees in each category based on the most recent municipal street tree data for each location. Under a scenario of less climate change (RCP 4.5), fewer than 2% of trees in each municipality were considered highly vulnerable across all 14 municipalities. Under a scenario of greater change (RCP 8.5), upward of 25% of trees were considered highly vulnerable in some locations. However, the number of vulnerable trees varied greatly by location, primarily because of differences in projected summer high temperatures rather than differences in species composition. Urban foresters can use this information as a complement to other more traditional considerations used when selecting trees for planting.

Keywords: climate change, hardiness zones, vulnerability, urban forest, street tree, inventory, adaptive capacity, midwest and great lakes

INTRODUCTION

Urban forests are being increasingly recognized for their important role in helping cities adapt to and mitigate climate change (Janowiak et al., 2021). Urban trees can also be impacted by climate change, facing highly variable environmental conditions that produce a wide range of growth responses based on species, site interactions, and climatic variability (Fahey et al., 2013;

North et al., 2018). The effects of both urbanization and climate change can create significant challenges in managing future urban forests (Khan and Conway, 2020). As urban population increases, vegetation density tends to decrease contributing to the rise in surface temperatures by several degrees (Andersson et al., 2020). Rising temperatures from both land use change and climate change can lead to reductions in growth and indicators of stress such as crown dieback, dead branches, and epicormic growth (Zhang and Brack, 2021).

Climate change-induced stress on trees is amplified in urban environments, where the urban heat island effect, impervious surfaces, reduced air quality, and altered soils create conditions that can dramatically reduce growth and survival (Nowak et al., 2010). Urbanization can alter urban soil chemistry and microbial communities, reducing growth rates compared to trees planted in natural areas (Ward et al., 2021). The urban heat island effect combined with rising global temperatures can create conditions beneficial to insect pests, which may also be able to better take advantage of already-stressed urban trees (Tubby and Webber, 2010; Long et al., 2019). The increases in storm severity combined with growing space limitations has caused increased mortality of street trees (Johnson et al., 2019). Substantial crown dieback due to increases in drought and heatwave severity (Zhang and Brack, 2021) and reduced tree canopy increases the urban heat-related illness of residents, exacerbating existing inequalities in urban canopy distribution (Jung et al., 2021).

Climate change is also driving broadscale shifts in temperature and precipitation that can influence productivity and distribution of trees in both urban and natural systems (Vose et al., 2012). Precipitation and temperature during the growing season have been widely demonstrated as the primary climate variables influencing growth for most tree species globally (Kipfmueller et al., 2010; Dymond et al., 2016). Precipitation during the growing season also exhibits a strong positive relationship with urban tree growth (Cedro and Nowak, 2006; Monteiro et al., 2017). Precipitation during other parts of the year can also influence growth. Fall precipitation, for example, can also have positive effects on tree growth in the subsequent growing season (Romagnoli et al., 2018).

Increasing temperatures can have positive effects on growth, but only when these increases are relatively modest and when there is also sufficient moisture (Gustafson et al., 2017). High temperatures during the growing season can reduce urban tree growth, particularly during periods of low precipitation resulting in low levels of growth during warm, dry periods (McLaughlin et al., 2003; Cedro and Nowak, 2006; Zweifel et al., 2006; Monteiro et al., 2017). Work in forested settings has demonstrated the influence that local site conditions have on climate sensitivity within a tree species (Gewehr et al., 2014). Given the range of growing environments in urban areas, an understanding of the impacts of local growing conditions on climate response of urban trees is critical for evaluating the vulnerability of urban forests to future global change.

Urban trees have shown a reduced life span and increased maintenance costs due in part to climate stressors (Zhang and Brack, 2021). Risk assessment of urban trees, assessing the likelihood of failure and consequences due to the presence

of defects in trees, is critical for those responsible for the management of urban forests (Miller et al., 2015). Decay is a chronic defect that is associated with whole or partial tree failures (Smiley and Fraedrich, 1992; Mattheck et al., 1993; Terho and Hallaksela, 2008). A tree's ability to minimize and contain decay in scaffold branches, trunks, and supportive roots is a function of its genetic potential and overall health (Shigo, 1984). Therefore, a decline in the overall health of urban trees due to heat and precipitation stresses will negatively impact their ability to minimize decay, becoming more vulnerable to failures due to wind, ice, and snow loading events.

The ability of urban trees to mitigate some of the deleterious effects of increased climate variability and climatic change (McPherson et al., 1997) will depend in part on maintaining large, mature, and healthy tree populations (McPherson, 2003). Planting urban trees can be an effective method to reduce the deleterious effects of the urban heat island (Abdulateef and Al-Alwan, 2021; Li et al., 2021). The increased challenges of tree planting in harsh urban conditions highlights the importance of understanding the selection of trees adapted to current and future climate conditions (Brandt L. et al., 2016; Janowiak et al., 2021). Projected changes in climate often focus on increases in mean temperature; however, projected increases do not necessarily preclude occasional low temperatures consistent with historical climate conditions, compounding the difficulty in tree species selection.

Future tree species selection is crucial for developing an urban forest resilient to changes in climate. Wood and Dupras (2021), found planting trees species currently represented in the tree canopy provided fewer services in terms of avoiding water run-off, reduced heating costs, and air pollution removal under future urban conditions than if selecting a future-adapted species palette. Increasing species diversity over current levels also showed a reduced overall susceptibility to potential future pests (Wood and Dupras, 2021).

Climate change vulnerability assessments can be used to assess risks and adaptations in urban tree species. Vulnerability assessments have been used extensively in adaptation planning, including urban forests (Ordonez and Duinker, 2015; Brandt L. et al., 2016; Steenberg et al., 2017a,b). These studies provide important information about the vulnerability of the entire urban forest to climate change, including organizational and social factors that influence urban forest stewardship. However, few studies have examined the vulnerability and adaptability of individual urban trees to future climate conditions, and those that do exist are for only individual cities or a small subset of species (Brandt et al., 2017, 2020; Khan and Conway, 2020). A more comprehensive approach can aid urban foresters in identifying which species are at risk across geographies.

The goal of this study was to develop a standardized method for assessing vulnerability of urban trees across cities, with a focus on the United States Upper Midwest. We aimed to answer the following questions: (1) How vulnerable are urban tree populations to projected changes in climate? (2) How much does this vulnerability vary across cities?, and (3) What factors contribute to these differences?

MATERIALS AND METHODS

Tree Inventories

We collected the most recent municipal street tree inventories from 14 municipalities in Michigan, Wisconsin, and Minnesota, representing a range of geographic regions and sizes (**Table 1**). Inventory data was restricted to public trees planted on rights-of-way that were part of a municipality's official complete street tree inventory (not a sample). Only inventories that identified trees to the species level were used. Inventories varied in additional data included in inventories (e.g., diameter at breast height, condition class), so we focused specifically on species abundance as a common variable across cities. We eliminated species that composed less than 0.05% in all inventories to simplify the analysis. In addition to existing street trees, we evaluated species that are currently recommended for planting in southern Midwestern cities as potential new species for the Upper Midwest. Recommended planting lists were obtained from Des Moines, IA, St. Louis, MO, and Kansas City, MO.

Vulnerability Framework

Climate change vulnerability assessments typically define vulnerability as a function of exposure, sensitivity, and adaptive capacity (Intergovernmental Panel on Climate Change (IPCC) Working Group II, 2014). We used this general definition of vulnerability to develop a framework for assessing vulnerability of urban tree species (**Figure 1**). Exposure, the degree which a species or system is exposed to a climate hazard, was defined as the projected shift in USDA Hardiness Zones (USDA, 2012) and American Horticultural Society (AHS) Heat Zones (Brickell, 2011). The sensitivity of that species to the hazard was defined as the zones in which that species is suitable for planting. Adaptive capacity, or the species ability to cope with change, was defined as

TABLE 1 | Cities included in vulnerability analysis.

Municipality	Pop. Size	Median Income	Mean Annual Temp. (°C)	Mean Annual Precip. (mm)	Area (km^2)	Species evaluated	Trees inventoried
Ann Arbor, MI	120,641	$63,956	9.1	861.3	73	129	51,413
Ashland, WI	7,963	$40,433	4.8	857.0	34	61	4,308
Detroit, MI	677,155	$29,481	10.3	875.3	359	133	152,235
Grand Rapids, MI	197,081	$47,173	9.6	1004.8	115	116	73,735
Green Bay, WI	104,818	$47,797	7.6	805.7	117	89	34,989
Middleton, WI	19,235	$74,141	8.2	947.4	24	74	9,790
Milwaukee, WI	596,886	$40,036	9.6	878.1	249	100	210,342
Minneapolis, MN	416,021	$58,993	8.3	805.4	140	127	208,809
Monroe, WI	10,636	$46,685	8.6	965.5	13	50	4,674
Racine, WI	77,576	$42,767	8.7	896.4	41	86	24,515
Rochester, MN	113,913	$70,749	7.1	891.5	141	54	41,292
Saint Louis Park, MN	48,423	$75,690	8.3	805.4	27	57	19,444
Saint Paul, MN	302,760	$55,085	8.3	805.4	135	112	126,233
Stevens Point, WI	26,402	$45,040	6.6	849.6	44	79	1,866

Population and median income were retrieved form the United States Census. Mean annual temperature and precipitation data (1990–2019) was retrieved for each location from NOAA Climate At-A-Glance https://www.ncdc.noaa.gov/cag/.
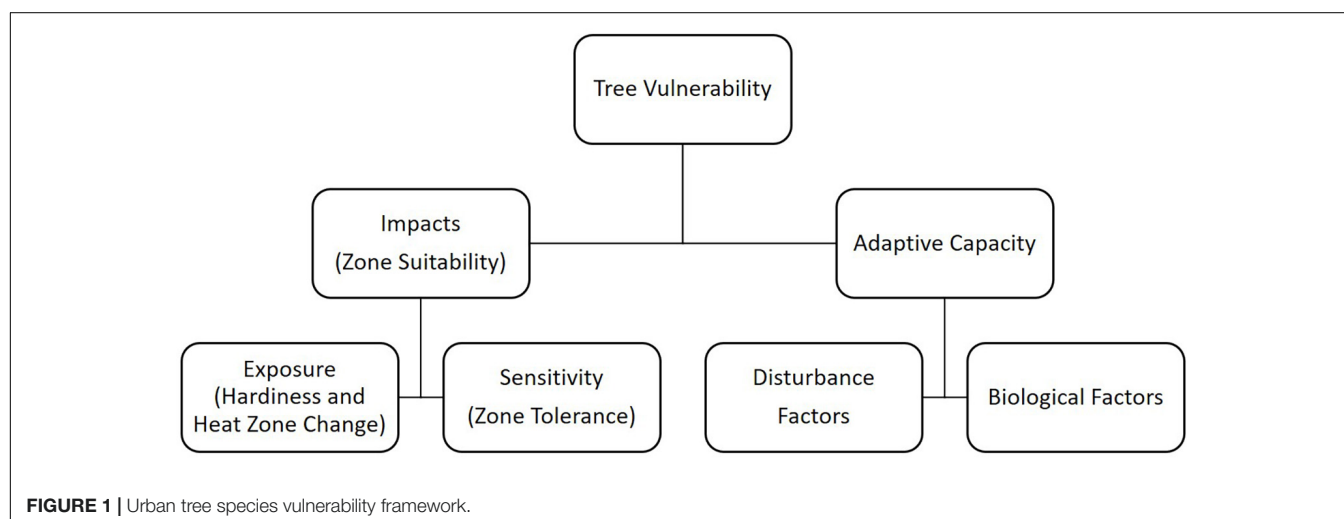

FIGURE 1 | Urban tree species vulnerability framework.

TABLE 2 | Adaptive capacity score factors for trees in planted environments.

Factor Type	Mod Factor	Code	Mod Factor Description
Disturbance	Disease	DISE	Accounts for the number and severity of known pathogens that attack a species. Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 2.
Disturbance	Insect Pests	INS	Accounts for the number and severity of insects that may attack a species. Defaults: Score = −2, Uncertainty = 0.5, Future Relevance = 4.
Disturbance	Browse	BRO	The extent to which browsing (by deer or other herbivores) affects the species, either positively by promoting growth or by effective strategies for herbivory avoidance, or negative by over-browsing. Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 1.
Disturbance	Invasive Plants	INPL	The effects of invasive plants on the species, either through competition for nutrients or as a pathogen. Defaults: Score = 0, Uncertainty = 0.5, Future Relevance = 4.
Disturbance	Drought	DRO	The degree to which a species is tolerant or susceptible to drought. Defaults for all species are: Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 3.
Disturbance	Flood	FLO	The degree to which a species is tolerant or susceptible to flooding. Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 3.
Disturbance	Ice	ICE	The damaging effects of ice storms and potential for ice heaving on a species. Defaults: Score = −1, Uncertainty = 0.5, Future Relevance = 2.
Disturbance	Wind	WIN	The damaging effects of windstorms and uprooting potential (and top breakage) of a species. Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 2.
Disturbance	Temperature Gradients	TEM	The effects of variations in the temperature gradient associated with a species Defaults: Score = 1, Uncertainty = 0.75, Future Relevance = 2.
Disturbance	Air Pollution	AIP	Airborne pollutants that affect, mostly negatively, a species' growth, health, and distribution. Includes acid rain, ozone. Defaults: Score = −2, Uncertainty = 0.75, Future Relevance = 3.
Disturbance	Soil and Water Pollution	SWP	Pollutants in the soil and water that affect, mostly negatively, a species' growth, health, and distribution. Defaults: Score = −2, Uncertainty = 0.5, Future Relevance = 1.

(Continued)

TABLE 2 | (Continued)

Factor Type	Mod Factor	Code	Mod Factor Description
Disturbance	Salt	SAL	The tolerance of a species to salt. This may include road salt and other urban salt pollution in soils, as well as sea spray for coastal areas. Defaults: Score = −2, Uncertainty = 0.5, Future Relevance = 1.
Biological	Competition-Light	COL	The tolerance of a species toward shade. Defaults: Score = 0, Uncertainty = 0.5, Future Relevance = 1.
Biological	Edaphic Specificity	ESP	The specific soil requirements (e.g., pH, texture, organic content, horizon thickness, permeability) for a species to survive in a suitable habitat. Includes long-term soil moisture capacities of the soil. Defaults: Score = 0, Uncertainty = 0.75, Future Relevance = 3.
Biological	Landscape and Planting Site Specificity	LPS	The ability for the species to be planted in a variety of site types (street, residential, park, campus). Defaults: Score = 0, Uncertainty = 0.75, Future Relevance = 3.
Biological	Restricted Rooting Conditions	RRC	The ability of a species to grow and survive in narrow boulevards and other constrained spaces. Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 3
Biological	Nursery Propagation	NUP	The ease and/or cost of producing the species in a nursery. Also relates to how widely available it is. Defaults: 0, Uncertainty = 0.75, Future Relevance = 4.
Biological	Planting Establishment	PLE	The ease with which the species establishes itself after planting. Also relates to the amount of care required to establish. Defaults: Score = 1, Uncertainty = 0.75, Future Relevance = 2.
Biological	Maintenance Required	MAR	The degree to which pruning or other maintenance is needed after establishment. Defaults: Score = −1, Uncertainty = 0.75, Future Relevance = 2.
Biological	Invasive Potential	INPO	Likelihood the species could become invasive if planted. Applies to both native and non-native species. Score = 0, Uncertainty = 0.75, and Future Relevance = 3. If species is known to be invasive, Score = −3 with the assumption that it will not be selected for future plantings.

a function of its ability to withstand disturbances such as drought and flooding and its biological adaptations that allow it to survive in a variety of growing conditions in an urban environment. This framework was designed to focus specifically on trees using data which is consistent across communities with the exception of future temperatures, and thus did not include other factors that can vary across communities such as socioeconomic

indicators or tree condition or age. Other frameworks have been developed to assess the vulnerability of urban forests systems that incorporate socioeconomic indicators (e.g., Ordonez and Duinker, 2014, 2015). Additionally, urban forest managers will have to account for local factors that may affect vulnerability of individual trees such as age, condition, or planting site.

Zone Suitability

Suitability for planting in each municipality was determined by a species tolerance to current and future projected United States Department of Agriculture Hardiness Zones and American Horticultural Society Heat Zones. Hardiness zones are widely used by growers and gardeners in the United States for selecting which species can be planted in a given location. They are calculated based on the average annual extreme minimum temperature. Zone 1 (-51 to $-48°C$) is the coldest hardiness zone, and zones increase by one integer for each $5.5°C$ of temperature. Heat Zones were developed by the American Horticultural Society based on the number of days above $30°C$. Heat zones range from 1 (less than 1 day above $30°C$) to 12 (more than 210 days above $30°C$).

Current (1980–2009) and future projected (2010–2039, 2040–2069, and 2070–2099) heat and hardiness zones under two future climate scenarios ("low" and "high") were obtained from the dataset described in Matthews et al. (2018). Hardiness and heat zone data were calculated from statistically downscaled daily maximum and minimum values at a one-eighth degree resolution ($\sim$13.875 $\times$ 13.875 km) (Maurer et al., 2007). For the "low" scenario, the Community Climate System Model (Gent et al., 2011), a general circulation model with relatively low sensitivity to CO_2 was paired with the RCP 4.5 storyline of relatively rapid reduction of greenhouse gases (Moss et al., 2008). Given that urban areas already can be several degrees hotter than their surrounding landscape and the current rate of greenhouse gas emissions, we did not include an RCP that simulates an even more dramatic reduction in carbon dioxide (e.g., RCP 2.6). For the "high" scenario, we used the Geophysical Fluid Dynamics Laboratory (GFDL) CM3 model (Donner et al., 2011) with the RCP 8.5 storyline of continued emissions increases throughout the 21st century.

A species was considered suitable for planting in a location if (1) its minimum hardiness zone tolerance was at or below the lowest hardiness zone at that location currently and for the 3 projected time periods and (2) its maximum heat and hardiness zone tolerance was at or above the maximum projected hardiness

and heat zone at that location currently and for the 3 projected time periods. We determined zone suitability for each species in each municipality for both the low (RCP 4.5) and high (RCP 8.5) emissions pathways.

Adaptive Capacity

To assess adaptive capacity, we developed qualitative scores using the methods described for trees in planted environments in Brandt et al. (2017), which builds on a framework for assessing adaptability for native trees developed by Matthews et al. (2011). The scoring system includes 20 Modification Factors (Mod Factor), divided into two Factor Types: Disturbance and Biological (Table 2). Disturbance factors affect a species' ability to resist or bounce back from disturbances whereas Biological factors are traits that affect nursery production, establishment, growth, and long-term maintenance.

Each Mod Factor is given a score, ranging from -3 (negative effect on establishment, growth, or survival) to $+3$ (positive effect on establishment, growth, or survival), that relates to the potential influence a Mod Factor has on the species throughout its range at the present. Each Mod Factor is weighted by two multipliers: Uncertainty and Future Relevance. Uncertainty is the degree of certainty (based on research and observation) about the factor's influence on the species' establishment, growth, or long-term survival. Uncertainty multipliers range from 0.5 = highly uncertain; 0.75 = somewhat uncertain; to 1.0 = high certainty. Future Relevance is the likely future relevance that a particular Mod Factor could have on the establishment, growth, or survival of a species over the next 50 years in a changing climate. Future Relevance multipliers range from 1 = not highly relevant over the next 50 years to 5 = likely to be extremely important.

To assign scores, information about each species was compiled and summarized from existing horticultural databases, street tree manuals, and silvics literature. The majority of information was summarized from Gilman and Watson (1993) with supplementation from Burns and Honkala (1990). Hauer et al. (2006) and Duryea et al. (2007) were used as supplementary references on ice and wind tolerance, respectively. When information could not be found from these sources, we consulted state extension and arboretum websites. Qualitative descriptions of each factor for each species were summarized based on the consensus from these sources and converted to a numerical score based on the degree of influence the factor had on the species' growth and long-term survival. When there was insufficient information in the literature, a species was assigned a default score and lower certainty (see Table 2).

Raw and weighted sub-scores were developed for both Disturbance and Biological Mod Factors. Additionally, an Adaptive Capacity score was calculated by the following equation:

$$D^2 + B^2 = A^2$$

where D is the raw Disturbance sub-score, B is the raw Biological sub-score, and A is the Adaptive Capacity score. Adaptive Capacity scores were then assigned to 3 categories: High (>4.5), Moderate (>3.5 and ≤ 4.5), and Low (≤ 3.5). The cut-off points

TABLE 3 | Vulnerability matrix used to assign species to vulnerability categories based on zone suitability and adaptive capacity.

Zone Suitability	High adaptive capacity	Moderate adaptive capacity	Low adaptive capacity
Suitable	Low vulnerability	Low-moderate vulnerability	Moderate vulnerability
Not Suitable	Moderate vulnerability	Moderate-high vulnerability	High vulnerability

were determined by plotting the distribution of the scores and assigning relatively equal-sized bins around the mean.

Expert Review

To verify the accuracy of both the suitability and Adaptive Capacity scores, we recruited 14 urban forestry and horticultural experts from the United States Upper Midwest. These experts were university faculty and extension specialists and botanical garden and arboretum collections staff with expertise in trees in the horticultural trade. Experts were from Minnesota, Iowa, Illinois, Wisconsin, North Dakota, and Michigan. Experts had advanced degrees in their area of expertise and multiple decades of experience in the field. Each species was assigned a minimum of two expert reviewers who had experience with growing and/or maintaining that species in the Midwest. The reviewers were given detailed instructions to review the species score, assigned Heat and Hardiness zone, and qualitative descriptions of a species Mod Factors given the supporting literature. If both experts agreed that a trait or zone tolerance was inaccurate, we adjusted the score to align with expert opinion. When experts disagreed, we deferred to the expert whose opinion most closely aligned with other existing literature.

Vulnerability

We combined the suitability ratings with adaptive capacity scores to assess species vulnerability under low and high emissions based on a vulnerability matrix (**Table 3**). We analyzed the number of species and the number of trees (based on inventory data) that fell into each vulnerability category for each municipality under each emissions pathway.
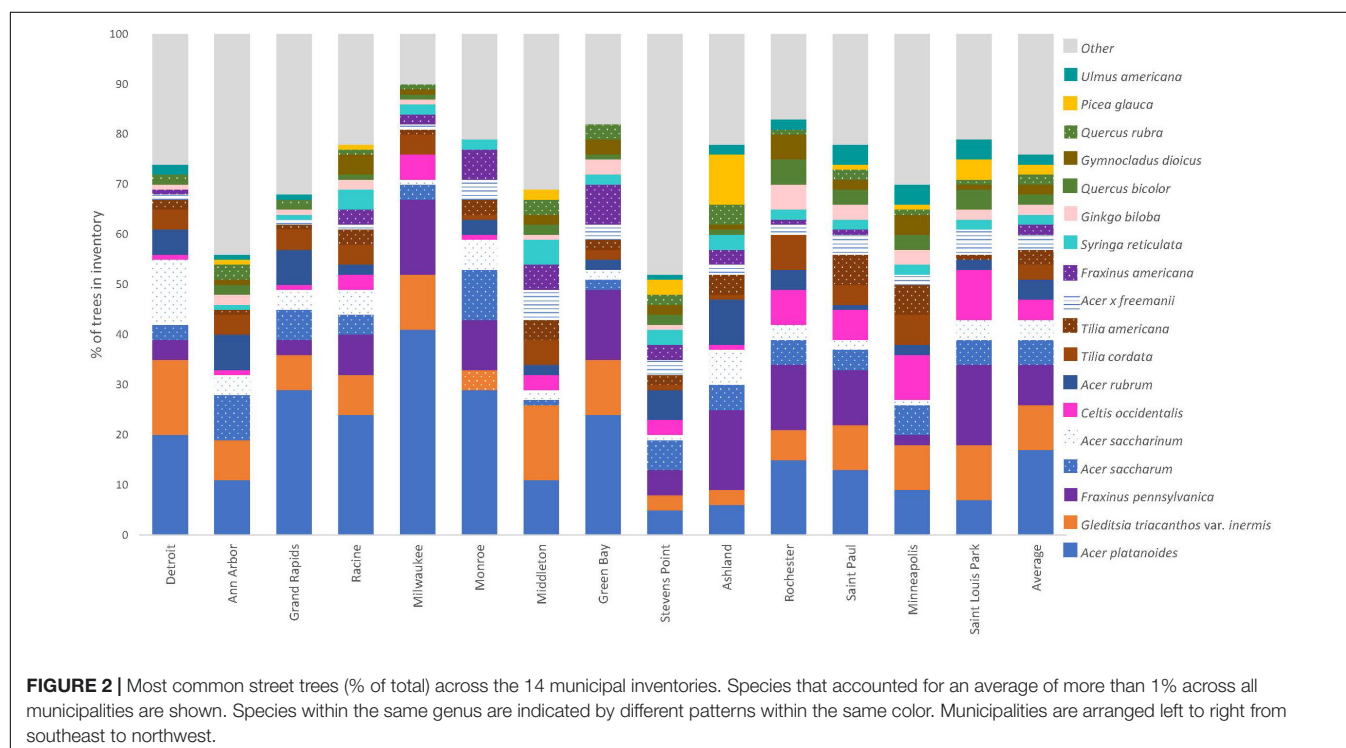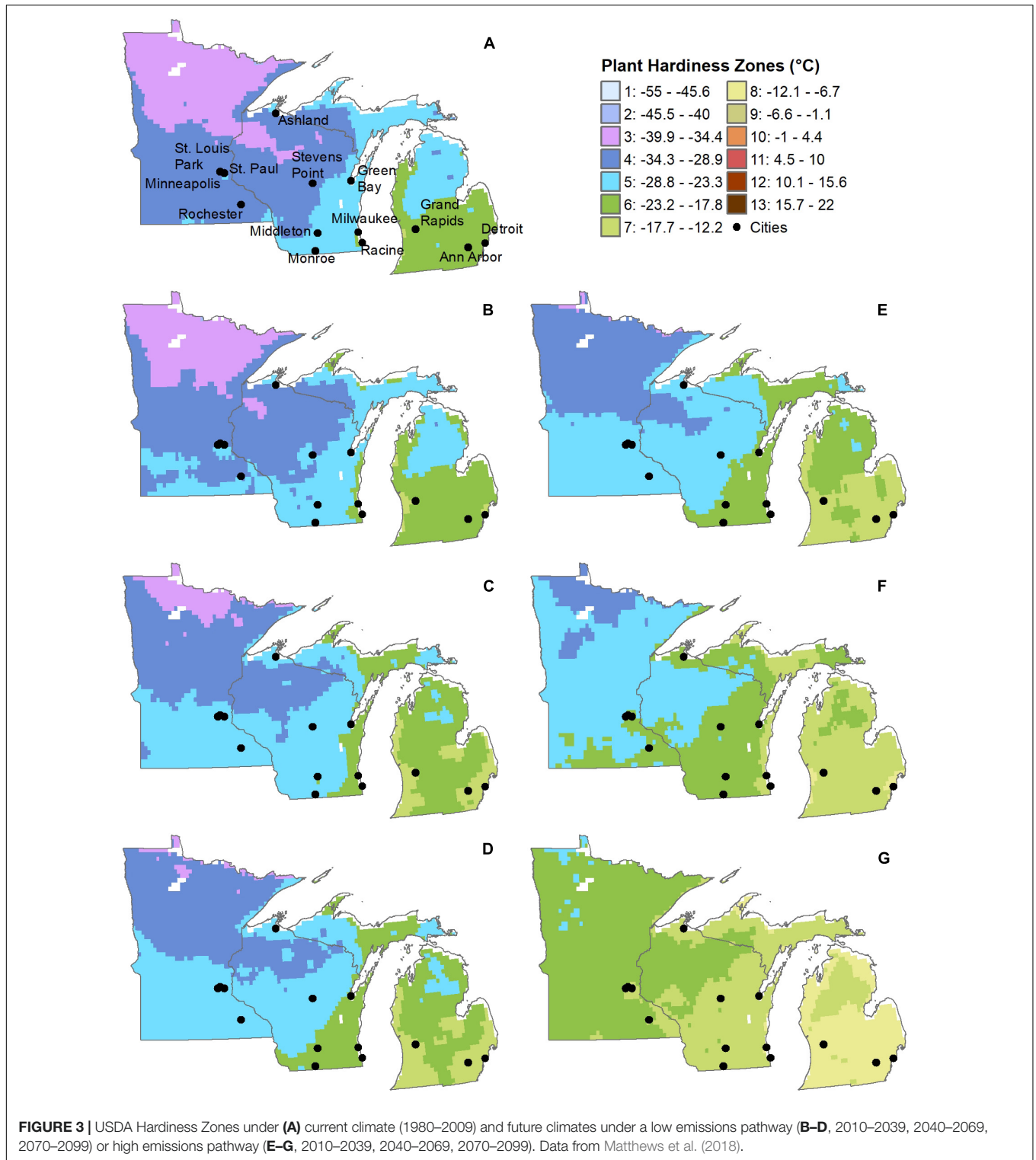
RESULTS

Tree Inventories

Averaged across all municipalities, *Acer platanoides* (a species native to Europe and considered invasive in the Midwestern United States) was the most common street tree, accounting for an average of 17% of street trees among the 14 municipalities (**Figure 2**). Species in the genus *Acer* accounted for 34% of inventoried trees on average. The next most common genus was *Fraxinus* (11%), followed by *Gleditsia*, *Quercus*, *Tilia*, *Ulmus*, *Celtis*, and *Picea*. The percent *Fraxinus* in the canopy has likely been reduced since these inventories were collected because of local infestations of emerald ash borer (*Agrilus planipennis*).

Projected Changes in Hardiness and Heat Zone Suitability

Current Hardiness Zones across the 14 municipalities range from 4 to 6, and are expected to shift to zones 5 to 7 under RCP 4.5 and 7 to 8 under RCP 8.5 (**Figure 3**). Heat Zones are projected to have a more dramatic shift from a current range of 3 to 5 to a projected range of 5 to 7 (RCP 4.5) to 8 to 9 (RCP 8.5, **Figure 4**). Of the 178 species evaluated, the number of potential species considered suitable for planting based on current and future heat and hardiness zones ranged from only 66 under RCP 8.5 in the Minnesota cities to 172 under RCP 4.5 in Racine, WI (**Table 4**). Municipalities that had both a warmer initial Hardiness Zone and less projected change in Heat Zones had more species that fell within current and projected ranges. Under the RCP 4.5 scenario, each species was suitable for planting in at least one city. Under RCP 8.5, 74 species were no longer considered

FIGURE 2 | Most common street trees (% of total) across the 14 municipal inventories. Species that accounted for an average of more than 1% across all municipalities are shown. Species within the same genus are indicated by different patterns within the same color. Municipalities are arranged left to right from southeast to northwest.

FIGURE 3 | USDA Hardiness Zones under **(A)** current climate (1980–2009) and future climates under a low emissions pathway (**B–D**, 2010–2039, 2040–2069, 2070–2099) or high emissions pathway (**E–G**, 2010–2039, 2040–2069, 2070–2099). Data from Matthews et al. (2018).
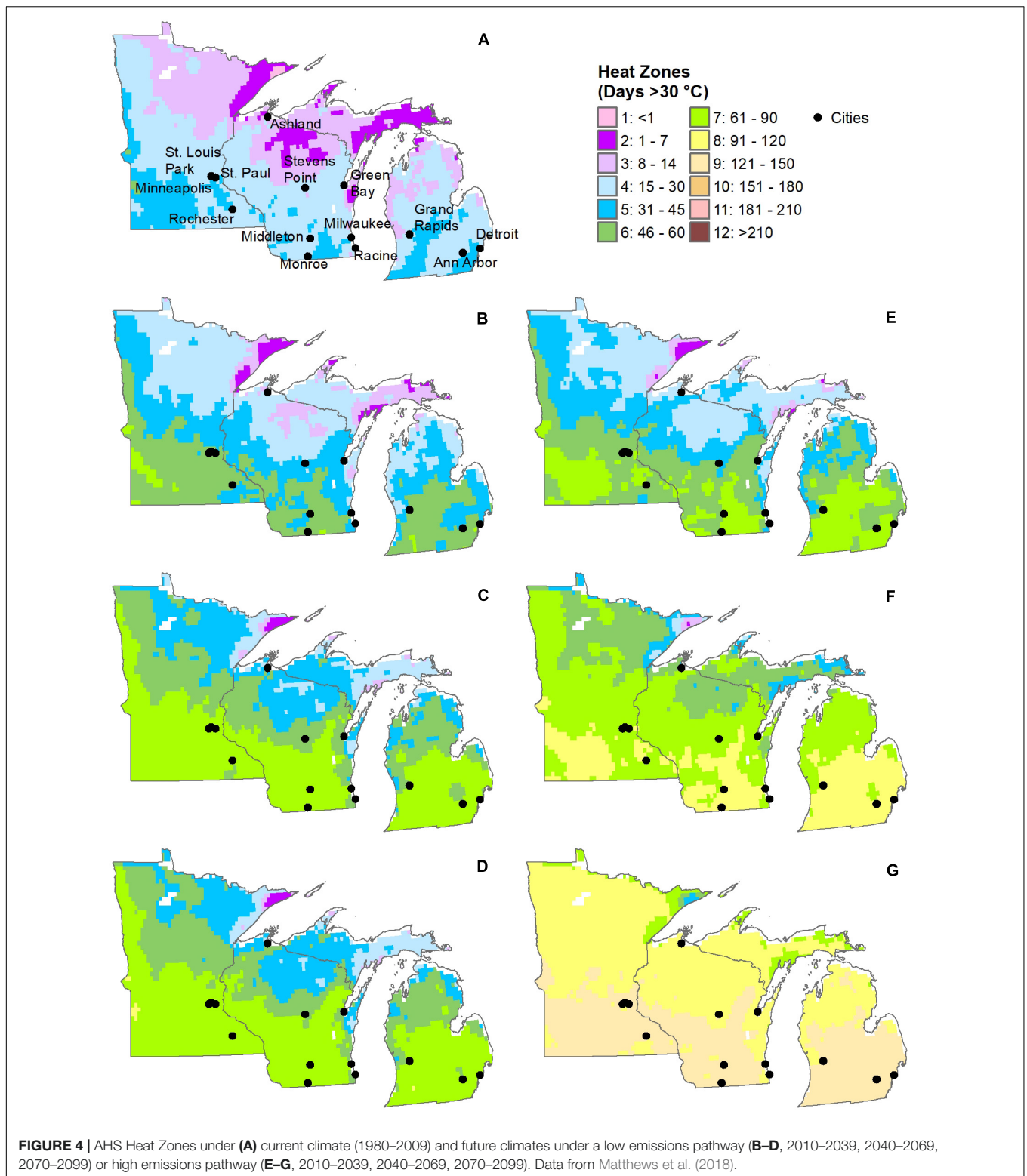
to be within the projected Hardiness Zone or Heat Zone ranges for any of the municipalities. Most of these were conifer species common to high latitudes or alpine areas, but *Acer platanoides* and *Syringa reticulata*, two commonly planted temperate species, also fell into this group.

Adaptive Capacity

Of the 178 species evaluated, 59 were considered to have high Adaptive Capacity, 94 had moderate Adaptive Capacity, and 25 had low Adaptive Capacity (see **supplementary materials**). Which species fell into each category did not change substantially

FIGURE 4 | AHS Heat Zones under **(A)** current climate (1980–2009) and future climates under a low emissions pathway (**B–D**, 2010–2039, 2040–2069, 2070–2099) or high emissions pathway (**E–G**, 2010–2039, 2040–2069, 2070–2099). Data from Matthews et al. (2018).

following expert review: expert review rather had an influence on contributing sub-factors (see **supplementary material** and numerical scores within categories). The species with the lowest Adaptive Capacity tended to be intolerant of disturbances such as drought and flooding and unable to tolerate urban conditions such as road salt and restricted rooting conditions. Examples included *Prunus serotina, Fraxinus nigra, Tsuga canadensis, Pinus resinosa, Pseudotsuga menziesii* var. *glauca, Juglans nigra,*

TABLE 4 | Number of species that are considered suitable for planting based on current and projected hardiness and heat zones in each municipality.

	RCP 4.5		RCP 8.5	
	Potential	Current	Potential	Current
Ann Arbor	172	125	82	55
Ashland	149	58	112	44
Detroit	172	126	82	59
Grand Rapids	172	113	82	47
Green Bay	171	84	139	67
Middleton	168	72	84	28
Milwaukee	172	96	86	42
Minneapolis	145	103	66	42
Monroe	168	49	84	22
Racine	175	85	143	54
Rochester	145	51	66	24
Saint Louis Park	145	55	66	25
Saint Paul	145	94	66	40
Stevens Point	148	73	112	52

Potential: total number of species out of the 178 evaluated. Current: number of species that are currently present in that municipality's inventory.

and *Pinus strobus*. The species with the highest adaptive capacity included *Ginkgo biloba*, *Ulmus* cultivars resistant to Dutch elm disease (*Ophiostoma novo-ulmi* and *O. ulmi*), as well as several species known for their invasiveness, including *Rhamnus cathartica, Quercus acutissima, Elaeagnus angustifolia,* and *Ailanthus altissima*. The number of trees in each category varied by municipality—Milwaukee had the most trees in the high Adaptive Capacity category (58%) and Ashland the least (20%). Cities had on average 7% of their trees in the low Adaptive Capacity category, with the most in Stevens Point (16%). These differences among municipalities were primarily due to planting more of a few highly adaptable or unadaptable species: all cities had the most species in the moderate adaptability category.

Vulnerability

Under a low emissions pathway (RCP 4.5), over 80% of trees in all municipalities were considered to have low or low-moderate vulnerability (**Figure 5A**). However, under the high emissions pathway (RCP 8.5), fewer than 50% of trees fell into either of these two vulnerability categories (**Figure 5B**). Monroe, WI, had the most trees in the moderate-high and high vulnerability categories and the fewest in the low vulnerability category under the high emission pathway. Racine and Green Bay, WI had the fewest trees in the moderate-high or high vulnerability categories. Ashland and Racine, WI, had the most trees in the low and low-moderate vulnerability category.

We averaged vulnerability scores across all locations to find the most and least vulnerable trees across the region. The 30 most common species, composing 87.5% of all inventories combined, primarily fell into the low or low-moderate category under RCP 4.5 and the low-moderate or moderate category under RCP 8.5 (**Table 5**). The most vulnerable common species were *Pyrus calleryana, Quercus palustris, Q. alba, Q. ellipsoidalis,* and *Picea glauca,* collectively composing 3.5% of all inventories combined.
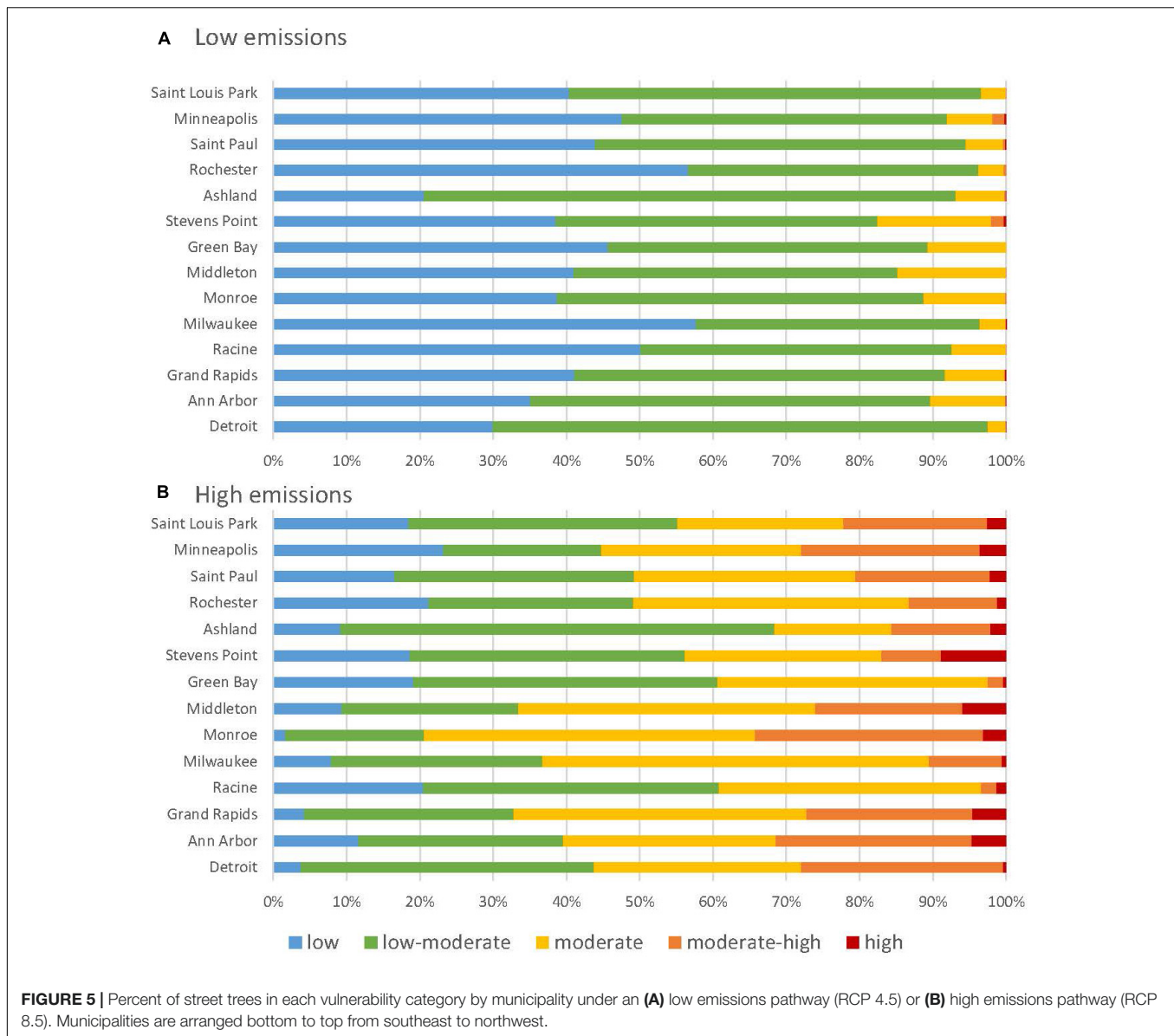
We also examined species and cultivars that were under-represented or not represented at all in the inventories as potential candidates for expansion in the urban tree canopy in the United States Upper Midwest. We considered a species to be under-represented if it fell into the bottom 50% of species when ranking species by abundance across all inventories. This corresponded to less than 0.06% of all species and fewer than 500 individuals present across all 14 inventories. Species were considered potential candidates for expansion if they had high Adaptive Capacity and had Hardiness Zone ranges within the projected ranges for the Upper Midwest. Any species that was listed as having the potential for being invasive was eliminated from the list. Twenty-nine species and cultivars from 16 genera met these criteria (**Table 6**). However, several of these species are from families and genera that already represent an overabundance of the total tree canopy.

DISCUSSION

This is the first study that systematically evaluates urban tree vulnerability across municipalities by combining projected changes in Hardiness and Heat Zones with expert-derived assessments of adaptive capacity. This study builds on methods we developed for individual cities (Brandt et al., 2017, 2020). Other studies have examined how Hardiness Zone shifts may affect tree habitat suitability across municipalities but have not incorporated important considerations of heat tolerance and adaptive capacity (Lanza and Stone, 2016). Others have developed comprehensive vulnerability assessments of urban forests but have not included the vulnerability of individual trees (Ordonez and Duinker, 2015).

Our results indicate that the most common species used in street tree planting can contribute to vulnerability. The most abundant trees in all municipalities evaluated were maples (genus *Acer*, family Sapindaceae), and one of the most dominant species in that genus (*Acer platanoides*) is potentially vulnerable in many of the municipalities evaluated. In addition, northern conifer species (genus *Picea* and *Pinus*) may also be vulnerable, and municipalities that plant a larger proportion of these species, such as Stevens Point, may also be at an increased vulnerability to warming temperatures. A recent study developed a vulnerability matrix for 27 species in the city of Mississauga, Ontario (43.6° N) also found *Acer platanoides* and northern conifers to be among the most vulnerable to increased temperatures (Khan and Conway, 2020), suggesting that these species may be at risk across North American temperate cities.

It is important to note that our study only examined species abundance and only in municipal trees planted along rights-of-way (also known as "street trees"). Other indicators of species dominance, such as total basal area or leaf area, may be more important in influencing ecosystem services at the municipal scale (Nowak et al., 2016). The composition of street trees is also not necessarily reflective of species composition in other municipal land use types such as remnant forests, commercial land, or residential properties (Bourne and Conway, 2014). Based

FIGURE 5 | Percent of street trees in each vulnerability category by municipality under an **(A)** low emissions pathway (RCP 4.5) or **(B)** high emissions pathway (RCP 8.5). Municipalities are arranged bottom to top from southeast to northwest.

on community inventory data from 14 Minnesota communities (Bancks et al., 2018), street trees only composed an average of 20% of a community's managed trees and ranged from 1 to 49% of a community's total tree population (data unpublished). For example, Pregitzer et al. (2019) found that remnant forests in New York were dominated by native species more similar in composition to natural systems than the composition of species along rights-of-way. Despite these limitations, street tree abundance is an important indicator of what species are being selected by local governments for planting. In addition, local tree planting initiatives, often led by non-profit organizations, tend to focus their attention on street trees because of a variety of constraints on planting in other locations (Salmond et al., 2016). Thus, street trees represent a large proportion of the total influence local decisionmakers in urban forestry have on future tree planting.

The greatest determinant of the vulnerability of a municipality's street tree canopy was its projected shift in Heat and Hardiness zones. Under a low emissions pathway (RCP 4.5), Hardiness and Heat zones were not projected to shift enough where trees would become vulnerable to temperature increases. Under a high emissions pathway (RCP 8.5), cities that were projected to shift to a heat zone 9 (>120 to 150 days exceeding 30°C) had more than 20% of their trees that were considered to be vulnerable (moderate-high or high category). Lanza and Stone (2016), examined shifts in Hardiness Zones in a national study that included Minneapolis-St. Paul and Detroit but did not find species in these cities to be at risk. This study examined a much smaller number of trees (51 and 69, respectively) and did not use downscaled climate data to project future Hardiness Zones (relying instead on historical data), nor did they examine Heat Zones. Thus, that study likely

TABLE 5 | Adaptive capacity and average vulnerability of the 30 most common species across all inventories in the study.

Scientific name	Common Name	% all inventories	Adaptive Capacity	Vulnerability RCP 4.5	Vulnerability RCP 8.5
Acer platanoides	Norway maple	21.2%	High	low	moderate
Gleditsia triacanthos var. *inermis*	Honeylocust	10.1%	Medium	low-moderate	low-moderate
Fraxinus pennsylvanica	Green ash	7.8%	Medium	low-moderate	low-moderate
Celtis occidentalis	Common hackberry	4.8%	High	low	low
Acer saccharum	Sugar maple	4.5%	Medium	low-moderate	moderate
Tilia cordata	Littleleaf linden	4.3%	High	low	low-moderate
Acer saccharinum	Silver maple	4.0%	Medium	low-moderate	moderate
Tilia americana	American linden	3.0%	Medium	low-moderate	moderate
Acer rubrum	Red maple	2.8%	Medium	low-moderate	low-moderate
Ginkgo biloba	Ginkgo	2.0%	High	low	low
Ulmus americana	American elm	2.0%	Medium	low-moderate	low-moderate
Quercus bicolor	Swamp white oak	1.9%	High	low	low-moderate
Acer × *freemanii*	Freeman maple	1.8%	High	low	low-moderate
Gymnocladus dioicus	Kentucky coffeetree	1.8%	High	low	low
Syringa reticulata	Japanese tree lilac	1.8%	High	low	moderate
Platanus × *acerifolia*	London planetree	1.6%	Medium	moderate	moderate
Quercus macrocarpa	Bur oak	1.3%	High	low	low
Fraxinus americana	White ash	1.3%	Low	moderate	moderate
Pyrus calleryana	Callery pear	1.3%	Medium	moderate	moderate-high
Quercus rubra	Northern red oak	1.3%	Medium	low-moderate	low-moderate
Platanus occidentalis	American sycamore	1.0%	Medium	low-moderate	low-moderate
Betula nigra	River birch	1.0%	Medium	low-moderate	low-moderate
Ulmus pumila	Siberian elm	0.9%	Medium	low-moderate	low-moderate
Catalpa speciosa	Northern catalpa	0.8%	Medium	low-moderate	moderate
Quercus palustris	Pin oak	0.7%	Medium	low-moderate	moderate-high
Quercus alba	White oak	0.6%	Low	moderate	moderate-high
Picea pungens	Colorado blue spruce	0.5%	Medium	low-moderate	moderate
Picea glauca	White spruce	0.5%	Medium	moderate	moderate-high
Ulmus americana 'Princeton'	Princeton elm	0.5%	High	low	low
Quercus ellipsoidalis	Northern pin oak	0.4%	Low	moderate	high

underestimates the true risk of these tree canopies to future extreme heat conditions.

Selection of certain species and groups of species for planting also played a role in determining vulnerability of a municipality's tree canopy. Minneapolis, St. Paul, and St. Louis Park provide an illustrative case study. These municipalities are directly adjacent and are projected to experience the same shifts in Hardiness and Heat Zones. Minneapolis has the most trees that fall into both the highest and lowest vulnerability categories. The most recent inventory had a greater abundance of Dutch elm-resistant *Ulmus* cultivars (low vulnerability) and a greater abundance of several northern conifer species (high vulnerability) compared with the other two cities. All three municipalities are in the process of replacing a large proportion of their tree canopy lost to emerald ash borer, so some of these differences may not be reflective of the current canopy composition in these cities.

To our knowledge, no other study has systematically evaluated such a large suite of species for their adaptive capacity. We evaluated 178 species and cultivars based on an already widely used method for evaluating species adaptive capacity (Matthews et al., 2011) that has been adjusted for urban systems and tested in previous assessments for individual

cities (Brandt et al., 2017, 2020). Realizing that information is limited for some of these species, having each adaptive capacity score independently reviewed by regional experts was essential to ensuring our scores reflected on-the-ground observations. For the most part, expert opinion was consistent with the established literature, but the reviews provided subtle differences in weighting of individual adaptive capacity factors.

Reducing the adaptive capacity of a species to a single qualitative value has its limitations, however. Information on some species traits that contribute to adaptive capacity is not always known and can limit our ability to develop strong indicators (Aubin et al., 2016). In addition, these qualitative scores are not related to any quantitative measure of the expected impact on species (e.g., its lifespan, growth rate, or mortality rate) and the relative contribution of traits and thresholds that determine what is vulnerable are somewhat arbitrarily determined by the assessor (Pacifici et al., 2015). For example, *Fraxinus pennsylvanica* is highly vulnerable to mortality from emerald ash borer, but its overall adaptive capacity score is relatively high due to its other traits. Likewise, a species may be considered to have high adaptive capacity because it currently does not have any pest or disease issues, but the arrival of a new

TABLE 6 | Species and cultivars with high adaptive capacity that are currently under-represented in upper Midwestern street tree inventories.

Scientific name	Common Name	Hardiness Range	Notable Adaptability Traits
Acer truncatum	Shantung maple	4–8	drought and heat tolerant
Amelanchier arborea	Downy serviceberry	4–9	wide temperature tolerance
Amelanchier laevis	Allegheny serviceberry	4–8	drought intolerant
Cornus kousa	Kousa dogwood	5–8	drought intolerant
Cotinus obovatus	Smoketree	4–8	drought tolerant, flood intolerant
Diospyros virginiana	Common persimmon	4–9	flood and drought tolerant
Eucommia ulmoides	Hardy rubber tree	4–7	drought tolerant, flood intolerant
Magnolia × soulangeana	Saucer magnolia	4–9	drought and flood intolerant
Nyssa sylvatica	Black gum	5–9	flood tolerant
Parrotia persica	Persian parrotia	5–8	drought tolerant, intolerant of salt
Pinus cembra	Swiss stone pine	3–7	drought tolerant, flood intolerant
Prunus "Okame"	Okame cherry	6–8	no notable negative of positive traits
Prunus maackii	Amur chokecherry	3–7	heat intolerant
Quercus imbricaria	Shingle oak	4–8	drought tolerant, susceptible to oak wilt
Quercus montana	Chestnut oak	4–8	drought tolerant, susceptible to oak wilt
Quercus muehlenbergii	Chinkapin oak	4–7	drought tolerant
Quercus × warei	Regal prince oak	4–9	drought tolerant, susceptible to oak wilt
Quercus lyrata	Overcup oak	6–9	drought and flood tolerant
Styphnolobium japonicum	Japanese pagoda-tree	5–8	drought and salt tolerant, flood intolerant
Syringa pekinensis	Peking tree lilac	3–8	drought and disease tolerant, flood intolerant
Tilia × euchlora	Crimean linden	3–7	drought tolerant, Dutch elm disease resistant
Ulmus "Patriot"	Patriot elm	5–9	drought tolerant, Dutch elm disease resistant
Ulmus "Morton Glossy" (Triumph)	Triumph elm	4–7	drought tolerant, Dutch elm disease resistant
Ulmus "Morton" (Accolade)	Accolade elm	4–9	heat tolerant, Dutch elm disease resistant

(Continued)

TABLE 6 | (Continued)

Scientific name	Common Name	Hardiness Range	Notable Adaptability Traits
Ulmus americana "Princeton"	Princeton elm	3–9	drought, heat, salt, and flood tolerant, Dutch elm disease resistant
Ulmus americana "New Harmony"	New Harmony elm	4–9	drought, heat, salt, and flood tolerant, Dutch elm disease resistant
Ulmus americana "Jefferson"	Jefferson elm	5–9	drought, heat, salt, and flood tolerant, Dutch elm disease resistant
Ulmus americana "Valley Forge"	Valley Forge elm	5–9	drought, heat, salt, and flood tolerant, Dutch elm disease resistant
Ulmus parvifolia	Lacebark elm	5–9	drought and heat tolerant

pest could change that dynamic. In addition, qualitative scoring systems such as these do not account for the many complex and cascading interactions that can occur as the climate changes.

Assessing future species planting suitability based in part on Hardiness and Heat Zones also has its limitations. Data regarding true Heat and Hardiness tolerance ranges for species and cultivars is often lacking. These ranges are sometimes based on very limited information and may not reflect the reality of observation. In addition, species range limits are often determined by a variety of climatic and non-climatic factors. More complex models can create a more complete picture not illustrated by heat and hardiness zones alone (McKenney et al., 2007). However, parameterizing such models for many species is currently limited by a lack of empirical data.

We designed this study to explicitly address the vulnerability of individual trees, but we recognize this is only one component of the vulnerability of the overall urban forest to climate change (Reynolds et al., 2020). Urban forest vulnerability will also be determined by the structural and functional composition, economic considerations, maintenance practices, and the social and organizational capacity of each location (Ordonez and Duinker, 2014, 2015; Brandt L. et al., 2016; Steenberg et al., 2017a). Previous research has shown that in fact, the economic and organizational capacity of individual municipalities can have more of an influence on vulnerability than the direct impacts of climate change (Brandt L. A. et al., 2016).

Municipal foresters and others managing urban forests can use this vulnerability information in concert with other information about tree height, growing site conditions, aesthetics, and other factors to inform planting lists for individual municipalities. Some municipalities may wish to reduce the dominance of certain species that are considered to be vulnerable in favor of less common, less vulnerable trees. Many municipalities are already incorporating species vulnerability information into

their planting lists (Peterson et al., 2021). Which species are appropriate will depend on the specific species composition of that area and the current and projected Heat and Hardiness zones for that particular place.

CONCLUSION

Our study provides a framework for assessing urban tree vulnerability that is broadly applicable to temperate urban forests. Using this framework, we found that most street trees commonly planted in United States Upper Midwest municipalities are not vulnerable under a low emissions pathway, but a larger proportion of trees are likely to be vulnerable under a high emissions pathway. Differences in the number of vulnerable trees was driven more by projected changes in the number of hot days rather than differences in species composition. This has important implications for urban street tree selection in a changing climate.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

LAB and GRJ designed the study. LAB, GRJ, EAN, and AR wrote the manuscript. LAB developed methods and analyzed results. JF conducted the vulnerability scoring. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021. 721831/full#supplementary-material

REFERENCES

Abdulateef, M. F., and Al-Alwan, H. A. S. (2021). The effectiveness of urban green infrastructure in reducing surface urban heat island. *Ain. Shams Eng. J.* doi: 10.1016/j.asej.2021.06.012

Andersson, E., Haase, D., Scheuer, S., and Wellmann, T. (2020). Neighbourhood character affects the spatial extent and magnitude of the functional footprint of urban green infrastructure. *Landscape Ecol.* 35, 1605–1618. doi: 10.1007/s10980-020-01039-z

Aubin, I., Munson, A. D., Cardou, F., Burton, P. J., Isabel, N., Pedlar, J. H., et al. (2016). Traits to stay, traits to move: a review of functional traits to assess sensitivity and adaptive capacity of temperate and boreal trees to climate change. *Environ. Rev.* 24, 164–186. doi: 10.1139/er-2015-0072

Bancks, N., North, E. A., and Johnson, G. R. (2018). An analysis of agreement between volunteer-and researcher-collected urban tree inventory data. *Arboric. Urban For.* 44, 73–86. doi: 10.48044/jauf.2018.007

Bourne, K. S., and Conway, T. M. (2014). The influence of land use type and municipal context on urban tree species diversity. *Urban Ecosyst.* 17, 329–348. doi: 10.1007/s11252-013-0317-0

Brandt, L., Lewis, A. D., Fahey, R., Scott, L., Darling, L., and Swanston, C. (2016). A framework for adapting urban forests to climate change. *Environ. Sci. Pol.* 66, 393–402. doi: 10.1016/j.envsci.2016.06.005

Brandt, L. A., Butler, P. R., Handler, S. D., Janowiak, M. K., Shannon, P. D., and Swanston, C. W. (2016). Integrating science and management to assess forest ecosystem vulnerability to climate change. *J. Forest.* 115, 212–221. doi: 10.5849/jof.15-147

Brandt, L. A., Lewis, A. D., Scott, L., Darling, L., Fahey, R. T., Iverson, L., et al. (2017). *Chicago Wilderness Region Urban Forest Vulnerability Assessment and Synthesis: A Report from the Urban Forestry Climate Change Response Framework Chicago Wilderness Pilot Project.* Gen. Tech. Rep. NRS-168. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station, 142.

Brandt, L. A., Rottler, C., Gordon, W. S., Clark, S. L., O'Donnell, L., Rose, A., et al. (2020). *Vulnerability of Austin's Urban Forest and Natural Areas: A Report from the Urban Forestry Climate Change Response Framework.* Washington, DC: U.S. Department of Agriculture, Northern Forests Climate Hub, 82.

Brickell, C. (2011). *American Horticultural Society Encyclopedia of Plants and Flowers.* New York, NY: Penguin, 744.

Burns, R. M., and Honkala, B. H. (1990). *Silvics of North America. 1. Conifers; 2. Hardwoods. Agriculture Handbook 654.* Washington, DC: U.S. Department of Agriculture, Forest Service, 877.

Cedro, A., and Nowak, G. (2006). Effects of climatic conditions on annual tree ring growth of the *Platanus* x *hispanica* 'Acerifolia' under urban conditions of Szczecin. *Dendrobiology* 55, 11–17.

Donner, L. J., Wyman, B. L., Hemler, R. S., Horowitz, L. W., Ming, Y., Zhao, M., et al. (2011). The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. *J. Climate* 24, 3484–3519. doi: 10.1175/2011JCLI3955.1

Duryea, M. L., Kampf, E., and Littell, R. C. (2007). Hurricanes and the urban forest: I. Effects on southeastern United States coastal plain tree species. *Arboric. Urban For.* 33, 83–97.

Dymond, S. F., D'Amato, A. W., Kolka, R. K., Bolstad, P. V., Sebestyen, S. D., and Bradford, J. B. (2016). Growth-climate relationships across topographic gradients in the northern Great Lakes. *Ecohydrology* 9, 918–929. doi: 10.1002/eco.1700

Fahey, R. T., Bialecki, M. B., and Carter, D. R. (2013). Tree growth and resilience to extreme drought across an urban land-use gradient. *Arboric. Urban For.* 39, 279–285.

Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., et al. (2011). The community climate system model version 4. *J. Climate* 24, 4973–4991. doi: 10.1175/2011JCLI4083.1

Gewehr, S., Drobyshev, I., Berninger, F., and Bergeron, Y. (2014). Soil characteristics mediate the distribution and response of boreal trees to climatic variability. *Can. J. For. Res.* 44, 487–498. doi: 10.1139/cjfr-2013-0481

Gilman, E., and Watson, D. G. (1993). *680 Tree Fact Sheets*. Available online at: https://hort.ifas.ufl.edu/database/trees/trees_scientific.shtml (accessed July, 2021).

Gustafson, E. J., Miranda, B. R., De Bruijn, A. M. G., Sturtevant, B. R., and Kubiske, M. E. (2017). Do rising temperatures always increase forest productivity? Interacting effects of temperature, precipitation, cloudiness and soil texture on tree species growth and competition. *Environ. Modell. Softw.* 97, 171–183. doi: 10.1016/j.envsoft.2017.08.001

Hauer, R. J., Dawson, J. O., and Werner, L. P. (2006). *Trees and Ice Storms: The Development of Ice Storm–Resistant Urban Tree Populations. Joint Publication 06-1, College of Natural Resources, University of Wisconsin-Stevens Point, and the Department of Natural Resources and Environmental Sciences and the Office of Continuing Education, University of Illinois at Urbana- Champaign*. Illinois, IL: University of Illinois, 20.

Intergovernmental Panel on Climate Change (IPCC) Working Group II (2014). "Climate change 2014: Impacts, adaptation, and vulnerability Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," in *IPCC Fifth Assessment Repor*, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (New York, NY: Cambridge University Press), 1132.

Janowiak, M. K., Brandt, L. A., Wolf, K. L., Brady, M., Darling, L., Lewis, A. D., et al. (2021). *Climate Adaptation Actions for Urban Forests and Human Health*. Gen. Tech. Rep. NRS-203. Madison, WI: US Department of Agriculture, Forest Service, Northern Research Station, 203.

Johnson, G., Giblin, C., Murphy, R., North, E., and Rendahl, A. (2019). Boulevard tree failures during wind loading events. *Arboric. Urban For.* 45, 259–269.

Jung, M. C., Dyson, K., and Alberti, M. (2021). Urban landscape heteorgenity influences the relationship between tree canopy and land surface temperature. *Urban For. Urban Gree.* 57:126930. doi: 10.1016/j.ufug.2020.126930

Khan, T., and Conway, T. M. (2020). Vulnerability of common urban forest species to projected climate change and practitioners perceptions and responses. *Environ. Manage.* 65, 534–547. doi: 10.1007/s00267-020-01270-z

Kipfmueller, K. F., Elliott, G. P., Larson, E. R., and Salzer, M. W. (2010). An assessment of the dendroclimatic potential of three conifer species in Northern Minnesota. *Tree-Ring Res.* 66, 113–126. doi: 10.3959/2009-12.1

Lanza, K., and Stone, B. (2016). Climate adaptation in cities: what trees are suitable for urban heat management? *Landscape Urban Plan.* 153, 74–82. doi: 10.1016/j.landurbplan.2015.12.002

Li, H., Zhou, Y., Jia, G., Zhao, K., and Dong, J. (2021). Quantifying the response of surface urban heat island to urbanization using the annual temperature cycle model. *Geosci. Front.* 101141. doi: 10.1016/j.gsf.2021.101141

Long, L. C., D'Amico, V., and Frank, S. D. (2019). Urban forest fragments buffer trees from warming and pests. *Sci. Total Environ.* 658, 1523–1530. doi: 10.1016/j.scitotenv.2018.12.293

Mattheck, C., Bethge, K., and Erb, D. (1993). Failure criteria for trees. *Arboric. J.* 17, 201–209.

Matthews, S. N., Iverson, L. R., Peters, M. P., and Prasad, A. M. (2018). *Assessing Potential Climate Change Pressures Across the Conterminous United States: Mapping Plant Hardiness Zones, Heat Zones, Growing Degree Days, and Cumulative Drought Severity Throughout this Century. RMAP-NRS-9*. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station, 31.

Matthews, S. N., Iverson, L. R., Prasad, A. M., Peters, M. P., and Rodewald, P. G. (2011). Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors. *Forest Ecol. Manag.* 262, 1460–1472. doi: 10.1016/j.foreco.2011.06.047

Maurer, E. P., Brekke, L., Pruitt, T., and Duffy, P. B. (2007). Fine-resolution climate projections enhance regional climate change impact studies. *EOS* 88, 504–504. doi: 10.1029/2007EO470006

McKenney, D. W., Pedlar, J. H., Lawrence, K., Campbell, K., and Hutchinson, M. F. (2007). Beyond traditional hardiness zones: using climate envelopes to map plant range limits. *Bioscience* 57, 929–937. doi: 10.1641/B571105

McLaughlin, S. B., Wullschleger, S. D., and Nosal, M. (2003). Diurnal and seasonal changes in stem increment and water use by yellow polar trees in response to environmental stress. *Tree Physiol.* 23, 1125–1136. doi: 10.1093/treephys/23.16.1125

McPherson, E. G. (2003). A benefit-cost analysis of ten street tree species in Modesto, California, U.S. *J. Arboric.* 29, 1–8.

McPherson, E. G., Nowak, D., Heisler, G., Grimmond, S., Souch, C., Grant, R., et al. (1997). Quantifying urban forest structure, function, and value: the Chicago urban forest climate project. *Urban Ecosyst.* 1, 49–61. doi: 10.1023/A:1014350822458

Miller, R. W., Hauer, R. J., and Werner, L. P. (2015). *Urban Forestry: Planning and Managing Urban Greenspaces*. Long Grove, IL: Waveland press, 560.

Monteiro, M. V., Levanic, T., and Doick, K. J. (2017). Growth rates of common urban trees in five cities in Great Britain: a dendrochronological evaluation with an emphasis on the impact of climate. *Urban. For. Urban Gree.* 22, 11–23. doi: 10.1016/j.ufug.2017.01.003

Moss, R. H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J. A., et al. (2008). *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Geneva: Intergovernmental Panel on Climate Change, 132.

North, E. A., D'Amato, A. W., and Russell, M. B. (2018). Performance metrics for street and park trees in urban forests. *J. Forest.* 116, 547–554. doi: 10.1093/jofore/fvy049

Nowak, D. J., Hoehn, R. E., Bodine, A. R., Greenfield, E. J., and O'Neil-Dunne, J. (2016). Urban forest structure, ecosystem services and change in Syracuse, NY. *Urban Ecosyst.* 19, 1455–1477. doi: 10.1007/s11252-013-0326-z

Nowak, D. J., Stein, S. M., Randler, P. B., Greenfield, E., and Comas, S. J. (2010). *Sustaining America's Urban Trees and Forests*. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, 27.

Ordonez, C., and Duinker, P. N. (2014). Assessing the vulnerability of urban forests to climate change. *Environ. Rev.* 22, 311–321. doi: 10.1139/er-2013-0078

Ordonez, C., and Duinker, P. N. (2015). Climate change vulnerability assessment of the urban forest in three Canadian cities. *Climatic Change* 131, 531–543. doi: 10.1007/s10584-015-1394-2

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., et al. (2015). Assessing species vulnerability to climate change. *Nat. Clim. Change* 5, 215–224. doi: 10.1038/nclimate2448

Peterson, C. L., Brandt, L. A., Elias, E. H., and Hurteau, S. R. (2021). Community forests prepare for climate change. *EOS* 102, 21–25. doi: 10.1029/2021EO154456

Pregitzer, C. C., Charlop-Powers, S., Bibbo, S., Forgione, H. M., Gunther, B., Hallett, R. A., et al. (2019). A city-scale assessment reveals that native forest types and overstory species dominate New York City forests. *Ecol. Appl.* 29:e01819. doi: 10.1002/eap.1819

Reynolds, H. L., Brandt, L., Fischer, B. C., Hardiman, B. S., Moxley, D. J., Sandweiss, E., et al. (2020). Implications of climate change for managing urban green infrastructure: an Indiana, US case study. *Climatic Change* 163, 1967–1984. doi: 10.1007/s10584-019-02617-0

Romagnoli, M., Moroni, S., Recanatesi, F., Salvati, R., and Mugnozza, G. S. (2018). Climate factors and oak decline based on tree-ring analysis. A case study of peri-urban forest in the Mediterranean area. *Urban For. Urban Gree.* 34, 17–28. doi: 10.1016/j.ufug.2018.05.010

Salmond, J. A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., et al. (2016). Health and climate related ecosystem services provided by street trees in the urban environment. *Environ. Health.* 15, 95–111. doi: 10.1186/s12940-016-0103-6

Shigo, A. L. (1984). Compartmentalization: a conceptual framework for understanding how trees grow and defend themselves. *Annu. Rev. Phytopathol.* 22, 189–214. doi: 10.1146/annurev.py.22.090184.001201

Smiley, E. T., and Fraedrich, B. R. (1992). Determining strength loss from decay. *J. Arboric.* 18, 201–204.

Steenberg, J. W. N., Millward, A. A., Nowak, D. J., and Robinson, P. J. (2017a). A conceptual framework of urban forest ecosystem vulnerability. *Environ. Rev.* 25, 115–126. doi: 10.1139/er-2016-0022

Steenberg, J. W. N., Millward, A. A., Nowak, D. J., Robinson, P. J., and Ellis, A. (2017b). Forecasting urban forest ecosystem structure, function, and vulnerability. *Environ. Manage.* 59, 373–392. doi: 10.1007/s00267-016-0782-3

Terho, M., and Hallaksela, A. M. (2008). Decay characteristics of hazardous *Tilia, Betula*, and *Acer* trees felled by municipal urban tree managers in the Helsinki City Area. *Forestry* 81, 151–159. doi: 10.1093/forestry/cpn002

Tubby, K. V., and Webber, J. F. (2010). Pests and diseases threatening urban trees under a changing climate. *Forestry* 83, 451–459. doi: 10.1093/forestry/cpq027

USDA (2012). *USDA Plant Hardiness Zone Map*. Available online at: https://planthardiness.ars.usda.gov/PHZMWeb/ (accessed October 10, 2019).

Vose, J. M., Peterson, D. L., and Patel-Weynand, T. (2012). *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the US Forest Sector*. General Technical Report PNW-GTR-870. Portland: Pacific Northwest Research Station, USDA Forest Service, 265.

Ward, E. B., Doroski, D. A., Felson, A. J., Hallett, R. A., Oldfield, E. E., Kuebbing, S. E., et al. (2021). Positive long-term impacts of restoration on soils in an experimental urban forest. *Ecol. Appl.* 31:e02336. doi: 10.1002/eap.2336

Wood, S. L. R., and Dupras, J. (2021). Increasing function diversity of the urban canopy for climate resilience: potential tradeoffs with ecosystem services? *Urban For. Urban Gree.* 58:126972. doi: 10.1016/j.ufug.2020.126972

Zhang, B., and Brack, C. L. (2021). Urban forest responses to climate change: a case study in Canberra. *Urban For. Urban Gree.* 57:126910. doi: 10.1016/j.ufug.2020.126910

Zweifel, R., Zimmermann, L., Zeugin, F., and Newberry, D. M. (2006). Intra-annual radial growth and water relations of trees: implications towards a growth mechanism. *J. Exp. Bot.* 57, 1445–1459. doi: 10.1093/jxb/erj125