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Which Tree Species Best Withstand Urban Stressors? Ask the Experts

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Abstract. Background: The importance of urban trees and their benefits to society are increasingly recognized. However, cities are a challenging environment for trees to grow and thrive. Current knowledge on tree vulnerabilities to existing urban stressors remains scarce and available only for a limited number of species and specific stressors. Methods: Using the Delphi method with urban forestry experts familiar with the studied area and a closed-ended questionnaire, we sought to elucidate the tolerance of commonly planted urban tree species in northeastern North America to multiple urban stressors—air pollution, soil compaction, de-icing salts, insects and diseases, strong winds, ice storms, snow, drought, and extreme temperatures—as well as to assess which characteristics may capture a species' ability to cope with these stressors. Results: *Ginkgo biloba*, *Gleditsia triacanthos*, *Quercus* spp., and *Ulmus* spp. were rated by urban forestry professionals as the most tolerant species in northeastern North America to the studied stressors. No species was listed as tolerant to all stressors. Furthermore, respondents disagreed on how a given species was likely to be affected by or respond to a given stressor. Conclusions: Our study provides a powerful approach to gaining difficult-to-obtain information on trees' vulnerabilities to environmental stressors and identifying the gaps that remain unaddressed. Our findings fill some of the gaps in our knowledge of city trees' vulnerabilities, which makes the approach useful in practice to inform the choice of tree species that could be planted across our cities to build more resilient urban forests.

Keywords. Delphi Method; Expert Knowledge; Resilience; Stress Tolerance; Tree Management; Tree Vulnerability; Urban Forestry; Urban Trees.

INTRODUCTION

Urban trees, including those lining streets, in city parks, and private yards, directly affect human populations by altering the social, economic, and aesthetic aspects of urban environments (Konijnendijk et al. 2006). In the pursuit of sustainability and climate change resilience, cities are investing in trees to support a wide range of benefits, such as improved air and water quality, reduced stormwater runoff, and cooler air temperatures, reducing the effect of the urban heat island by shading surfaces and through evapotranspiration (Endreny 2018; Wong et al. 2021).

However, trees have to face very challenging conditions in cities, such as air pollution, de-icings salts, soil compaction, and more extreme temperatures, which are harmful to trees and can increase tree mortality risk (Ordóñez and Duinker 2014; Hilbert et al. 2019; Czaja et al. 2020). For instance, air pollution directly impacts the growth of trees through damage to the photosynthetic systems and stomatal functioning, being a major limiting growth factor of urban trees (Locosselli et al. 2019). De-icing salts, used on streets and sidewalks, can alter the soil structure, decreasing its permeability and increasing the salinity levels, making the uptake of nutrients and water by trees more difficult (Ordóñez-Barona et al. 2018). Soil compaction in small tree pits severely limits the uptake of nutrients, water, and oxygen by the roots, after which root growth is hampered in terms of density, spread, and vigour (Correa et al. 2019).

Urban trees are also impacted by events that climate change is likely to exacerbate, such as increases in drought and heatwave severity, insects and diseases, as well as wind, ice, and snowstorms (Escobedo et al. 2009; Tubby and Webber 2010; Teskey et al. 2015; Khan and Conway 2020). Climate change may also interact synergistically with other stressors: warmer and wetter winters may enable more pests

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and diseases to become established, and hotter and drier summers may increase the vulnerability of trees to the impacts of insects and diseases (Dale and Frank 2017; Seidl et al. 2017). In addition, cities are becoming increasingly dense, with more impervious surfaces and less space for vegetation (Jim et al. 2018).

In this paper, we define stressor as an environmental factor, natural or anthropogenic, that acts as a debilitating agent (Odum et al. 1979), and tolerance of an environmental factor as the ability to maintain normal growth in the face of stress imposed by that factor (Simms 2000). This entails the perceived or actual ability of individuals or species to withstand stress without suffering severe growth reduction and irreversible damage. The effect of these stressors on the resilience of urban forests and the continued provision of ecosystem services may vary depending on the particular stressor and tree species (Huff et al. 2020). For instance, certain stressors, such as ice storms or pest outbreaks, can act as pulses (higher intensity, lower frequency, and shorter duration) which typically result in strong ecosystem responses over short response times. Other stressors can act as presses (lower intensity, higher frequency, and longer duration), such as soil compaction or drought, which persist over more extended periods (Grimm et al. 2017; Harris et al. 2018; Ossola et al. 2021). Therefore, to optimize the survival and growth of trees planted in cities, understanding the vulnerability of different species to multiple stressors is essential.

Furthermore, urban forest managers regularly rely on certain species, which may not be suited to the future climate (Esperon-Rodriguez et al. 2022). Therefore, species diversity is key to increasing the resilience of the urban forest to future abiotic and biotic stresses (Paquette et al. 2021). The planting of many different tree species to prioritize diversification, however, may increase mortality when trees are not suited to local conditions (Hilbert et al. 2019). In spite of the growing body of research into trees' potential vulnerability to climate change and other stressors present in urban areas (Sæbø et al. 2003; Roloff et al. 2009; Sjöman and Nielsen 2010; Yang et al. 2014; Conway and Vander Vecht 2015; Sjöman et al. 2015; Vogt et al. 2017; Khan and Conway 2020), there are still many gaps in our knowledge regarding which species can better tolerate each potential stressor or multiple stressors acting additively (e.g., new insects and diseases, temperature shifts, snow and ice loading).

In this study, we aimed to address these gaps in our understanding of the vulnerabilities of city trees by seeking the knowledge of experts (urban forestry professionals). We focused on common urban tree species in northeastern North America, and we sought to classify them according to their tolerance to multiple stressors—soil compaction, air pollution, insects and diseases, ice storms, snow, de-icing salts, strong winds, drought, and extreme temperatures—as well as to assess which characteristics may capture a species' ability to cope with these stressors. To do so, in the first part of our study, we used the Delphi method to elicit the opinions and consensus agreement from experts through iterative rounds. Then, in the second part of our study, we circulated a questionnaire through networks of researchers and practitioners working in the fields of arboriculture and urban forestry to gain access to more people and a more comprehensive range of opinions. Ultimately, we hope our approach, which we provide the means to replicate, will be a helpful tool to inform the choice of tree species suitable for urban environments and create more resilient urban forests.

MATERIALS AND METHODS

Cities and Urban Tree Inventories

We focused this project on common tree species across major cities in northeastern North America: Halifax, Montréal, Ottawa, Québec City, and Toronto, in Canada; and Boston, New York City, and Syracuse, in the United States. These cities are among the most populated in northeastern North America and have similar tree species composition (Nock et al. 2013; Yang et al. 2015; Cowett and Bassuk 2017). They are located in hardiness zones 5 to 7 (Daly et al. 2012; Natural Resources Canada 2016) and are characterized by a strong annual temperature cycle, with cold winters and warm summers.

After reviewing the inventories of public trees of the cities mentioned above, which included street trees and trees in public parks, we identified the 5 most abundant tree species in each municipality. We combined them into a single species list (Table 1), which we used in the closed-ended questionnaire. We limited our list to 20 tree species as long surveys can cause response fatigue and misclassification problems, and the last questions would have more probability of being answered wrongly (Egleston et al. 2011; Brace 2018). For the Delphi questionnaire, we

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Table 1. Tree species used in the closed-ended questionnaire (*n* = 20). For each city, the 5 most abundant tree species in the public tree inventory are listed. Within each city, species are listed alphabetically.

Halifax	Montréal	Ottawa	Québec City	Toronto	Boston	New York	Syracuse
Acer platanoides	*Acer platanoides*	*Acer platanoides*	*Acer platanoides*	*Acer platanoides*	*Acer rubrum*	*Acer platanoides*	*Acer negundo*
Amelanchier sp.	*Acer saccharinum*	*Acer rubrum*	*Acer saccharinum*	*Acer saccharinum*	*Acer saccharum*	*Gleditsia triacanthos*	*Acer platanoides*
Pyrus calleryana	*Fraxinus pennsylvanica*	*Acer saccharum*	*Fraxinus pennsylvanica*	*Gleditsia triacanthos*	*Prunus serotina*	*Platanus* × *acerifolia*	*Acer saccharum*
Tilia cordata	*Gleditsia triacanthos*	*Gleditsia triacanthos*	*Quercus rubra*	*Malus* sp.	*Quercus rubra*	*Pyrus calleryana*	*Rhamnus cathartica*
Ulmus americana	*Tilia cordata*	*Tilia cordata*	*Tilia cordata*	*Picea pungens*	*Tsuga canadensis*	*Quercus palustris*	*Thuja occidentalis*

started with open-ended questions to avoid influencing the experts' opinions; participants were asked to identify the species they consider tolerant or intolerant to the studied stressors without us intervening and creating bias (Connor Desai and Reimers 2019). The studied stressors—air pollution, soil compaction, insects and diseases, ice storms, de-icing salts, strong winds, drought, extreme temperatures, and snow—were selected based on previous studies (e.g., Gregg et al. 2003; Ordóñez and Duinker 2014; Vogt et al. 2017; Jim et al. 2018; Czaja et al. 2020; Huff et al. 2020). The list of stressors was the same in both surveys. We recognize that our list is not exhaustive, but we believe it captures many of the most common stress factors with relevance to the selection and management of urban trees in eastern North America.

This research project has been approved by the research ethics committee of Université du Québec en Outaouais (#782).

Survey Methodologies

We used 2 types of questionnaires and methodologies to collect information on vulnerabilities of trees to environmental stressors: the Delphi method, which began with an open-ended questionnaire (round 1) followed by rounds of feedback and modified questionnaires (rounds 2 and 3) that were given to a panel of selected experts, and a closed-ended questionnaire distributed to researchers and practitioners working in arboriculture and urban forestry. Our intention was not to directly compare the results of the 2 methodologies but rather to complement one with the other and provide a more general overview of the gaps in our knowledge or where there might be a lack of agreement. Term definitions were not given to participants (for example, stressor or tolerance).

Delphi Method

The Delphi method is a consensus-building technique based on iteration and feedback acquired from open-ended questionnaires given to a small group of experts who answer anonymously (Okoli and Pawlowski 2004; Chalmers and Armour 2019). This method differs from simple survey methods in that the population being surveyed is purposefully homogenous: the respondents are identified as experts, according to predefined criteria before the survey process begins, who are qualified to answer the questions (Okoli and Pawlowski 2004; Hallowell and Gambatese 2010). For the purposes of this study, experts were individuals working as urban foresters and arborists with 10 or more years of professional experience and expertise in cities across the Northeastern United States and Eastern Canada. The main advantages of the Delphi method are threefold: the anonymity of individual responses, which allows individuals to express their opinions without undue influence from their peers; the controlled feedback that enables individuals to reflect on the group perspective, thereby allowing for credible consensus; and the multiple iterations, which allows individuals to re-evaluate their opinions in the light of the controlled feedback of the overall group response (Okoli and Pawlowski 2004). The Delphi method has been widely used across research fields and for different purposes, including predicting the ecological impacts of climate change (Mukherjee et al. 2015), assessing

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the effects of tree management practices on ecosystem services in urban areas (Dupras et al. 2016), and understanding the values that drive the transformation of urban landscapes (Kalaycı Önaç and Birişçi 2019).

To reach out to the experts, we contacted several urban forestry-related networks by email, including the Society of Municipal Arborists, a professional association of arborists that specialize in the management of trees located in urban areas based in the United States; Tree Canada, the leading organization dedicated to planting and restoring tree cover in urban areas in Canada; as well as the parks and forestry departments of multiple northeastern North American cities. After recognizing potential participants, we asked them a set of screening questions to ensure that all participants met our eligibility criteria. In total, 40 individuals were contacted directly, of which 8 were invited and agreed to participate, but only 7 completed the 3 rounds of the study.

The questionnaire was designed on LimeSurvey (Schmitz 2003) and pilot-tested before final data collection. In the first round, respondents were asked to respond to open-ended questions about: (i) the effects of multiple stressors on urban trees; (ii) to list the 5 most tolerant and the 5 least tolerant species for each stressor; (iii) identify which characteristics may capture a species' ability to cope with these stressors; (iv) which stressors mentioned in the survey tend to interact the most with each other and increase the negative effects on trees; (v) what these effects might be; and (vi) which stressors they considered important and were not mentioned in the questionnaire. The answers that emerged from the responses from the first round were analyzed and summarized using content analysis techniques. Content analysis is a method designed to identify and interpret meaning in recorded forms of communication by providing structure in a large amount of textual data through a systematic process of interpretation (Kolbe and Burnett 1991). The content analysis was done manually and consisted of reading and re-reading the responses, developing a process of coding, categorizing, and summarizing the answers (Hsieh and Shannon 2005). These qualitative data were then translated into a structured questionnaire that formed the basis on which we constructed the second and third questionnaires sent to the expert panel (for more details, please see the Appendix). The experts were then asked to rate their agreement or disagreement with statements that emerged from the first round using a 5-point Likert scale. In the second round, statements for which 75% of the participants answered that they agree or strongly agree with that statement (i.e., ≥ 4 on the Likert scale) were considered consensual and omitted from the subsequent round. In the third round, the statements that had already reached consensus in prior rounds were omitted (75% agreement amongst respondents). Statements that had not yet achieved consensus were presented again, showing the group response (percentages) from the previous round. The experts were again asked to rate the statements on a 5-point scale and had the opportunity to revise and clarify their earlier answers if they chose to do so. The survey was stopped after the third round when consensus was reached on most statements. Data was collected for the 3 rounds of the Delphi survey between July 2020 and January 2021.

Closed-Ended Questionnaire

Secondly, we used a closed-ended questionnaire to complement the information gathered from the Delphi survey. The questionnaire was designed on LimeSurvey and pilot-tested before final data collection. This questionnaire targeted researchers and practitioners working in the fields of arboriculture and urban forestry. Prospective online participants were notified via email through networks of professional arborists and networks of students and researchers conducting research on urban forests. Interested individuals filled out a screening questionnaire to assess eligibility for the study. People were eligible if they had studied or worked in urban forestry in the studied geographical area. More details on the participants are summarized in the Appendix. There was no overlap in the participants included in the 2 surveys.

As explained above, a list of the most abundant species in the public tree inventories of the targeted cities was presented to respondents (Table 1). We limited our list to 20 species as long surveys can cause response fatigue, and as a result, attention to their responses and input can lapse. Respondents were asked to score each species on a 5-point scale according to their tolerance to the different stressors. A total of 98 people started the questionnaire, and 36 completed it. Of the 36 respondents, 31 had a university degree. Surveyed participants included academics (e.g., researchers and university professors) and practitioners (e.g., municipal arborists, and horticulture

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and arboriculture technicians). Data was collected between June 2020 and October 2020.

Data Analysis

Data from both surveys were analyzed using ranking techniques (Powell 2003). Means, standard deviations, and Kendall's coefficient of convergence (W) were calculated for each round to measure the concordance of opinions. The value of W ranges from 0 (no agreement) to 1 (complete agreement). According to Schmidt (1997), a weak consensus exists for $W < 0.3$, moderate for $W = 0.5$, and strong for $W > 0.7$. As for the most tolerant and intolerant species, in the first round of the Delphi survey, participants were asked to identify the 5 most tolerant and intolerant species to each stressor (free-text option). In rounds 2 and 3, participants were presented with 2 species lists based on the previous round and asked to rank those species from 1 (most tolerant/intolerant) to 5 (fifth most tolerant/intolerant). After the third round, the assigned ranking scores were averaged across experts to obtain a ranking score per species and stressor.

RESULTS

Findings from the Delphi Survey

The species most frequently cited as tolerant to the different stressors was *Gleditsia triacanthos*, cited as tolerant to 6 of the 9 studied stressors (Figure 1). It was followed by *Ginkgo biloba*, considered the most tolerant to air pollution, drought, insects and diseases, and extreme temperatures. Several species of the genus *Quercus*, namely *Q. alba* (QUAL), *Q. bicolor* (QUBI), *Q. macrocarpa* (QUMA), and *Q. rubra* (QURU), and the genus *Ulmus* were also considered

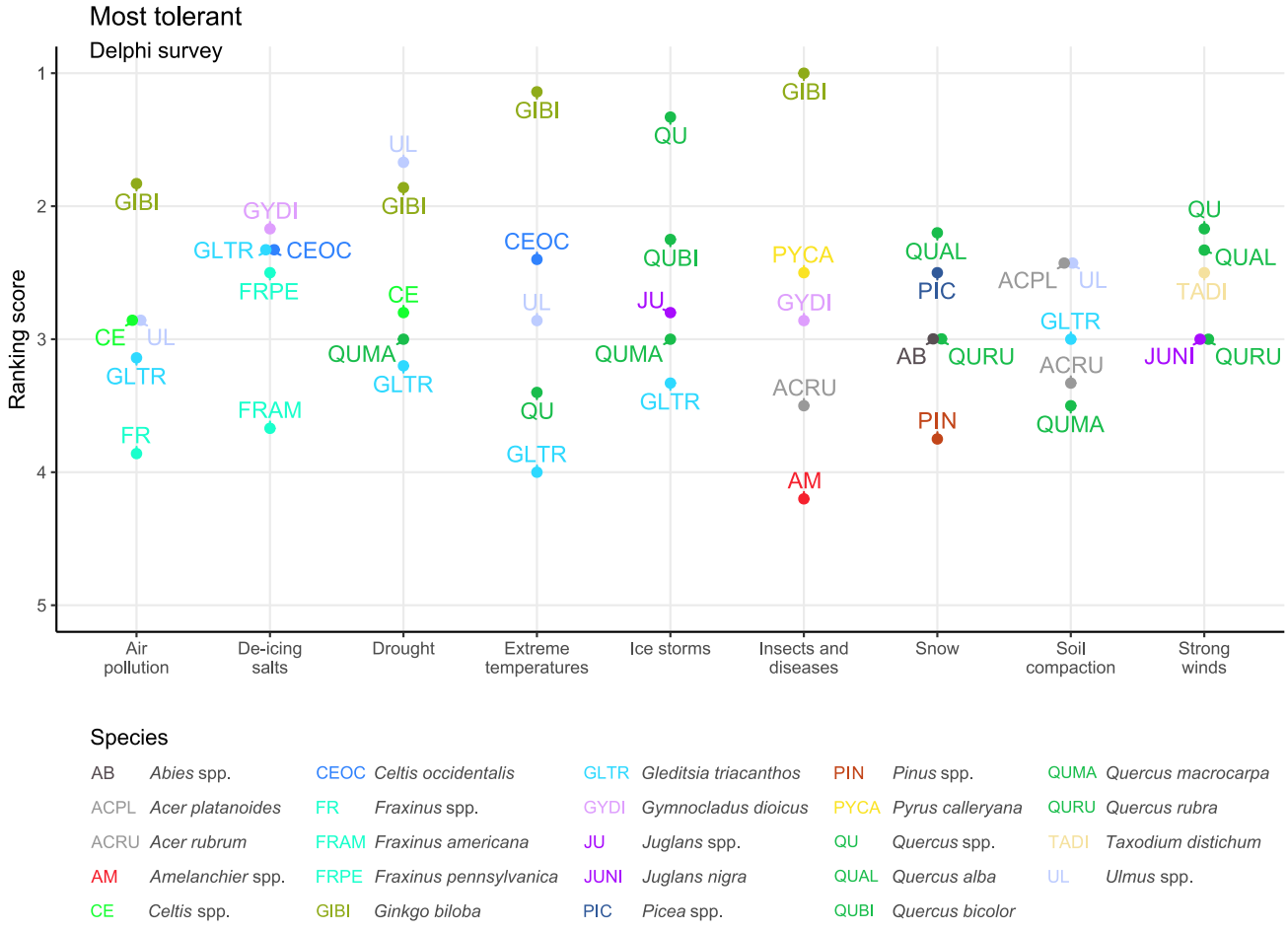

Figure 1. Ranking scores for the 5 species identified as the most tolerant to each studied stressor by the experts in the Delphi survey. The ranking score indicates agreement (or disagreement) with statements among experts ($n = 7$). The higher the ranking score, the higher the agreement regarding species tolerance. For instance, *Ginkgo biloba* was ranked first for air pollution with an average score of 1.83 on a scale of 1 (highest score) to 5 (lowest score), meaning that *G. biloba* was consensually regarded as tolerant to air pollution.

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tolerant to different stressors, viz. drought (QUMA), ice storms (QUBI, QUMA), snow (QUAL, QURU), soil compaction (QUMA), and strong winds (QUAL, QURU)(Figure 1). On the other hand, *Acer* spp., *Betula* spp., and *Pinus strobus* were identified as intolerant to 6 of the 9 studied stressors (Figure 2). According to the experts in the Delphi survey, urban trees tolerant to soil compaction are also adapted to salt stress and drought conditions.

Through the 3 rounds of the Delphi survey, the experts agreed that the stressors that interact the most with each other, thus aggravating their effects on urban trees, are: wind, ice, and snow, causing branch breakage; extreme temperatures and drought, causing heat and drought stress; soil compaction and de-icing salts, causing reduced water and nutrient uptake, slower root growth, and eventually tree death; drought and soil compaction, causing reduced water and nutrient uptake; and drought and insects and diseases, causing an increase of fungal infections and drought stress.

Other stressors that were not included in the questionnaire but that experts considered important in urban areas were human impact (e.g., construction work with deep excavation), mechanical damage (e.g., from street sweeping machines), absence of basic conditions for tree establishment and growth, poor water quality, and changes in the soil pH. A detailed discussion of the tree characteristics suggested by the experts as relevant to species' tolerance and intolerance to the studied stressors is presented in the Discussion section (see also Appendix).

Findings from the Closed-Ended Questionnaire

In the closed-ended questionnaire, from the list of species most abundant across major cities in northeastern

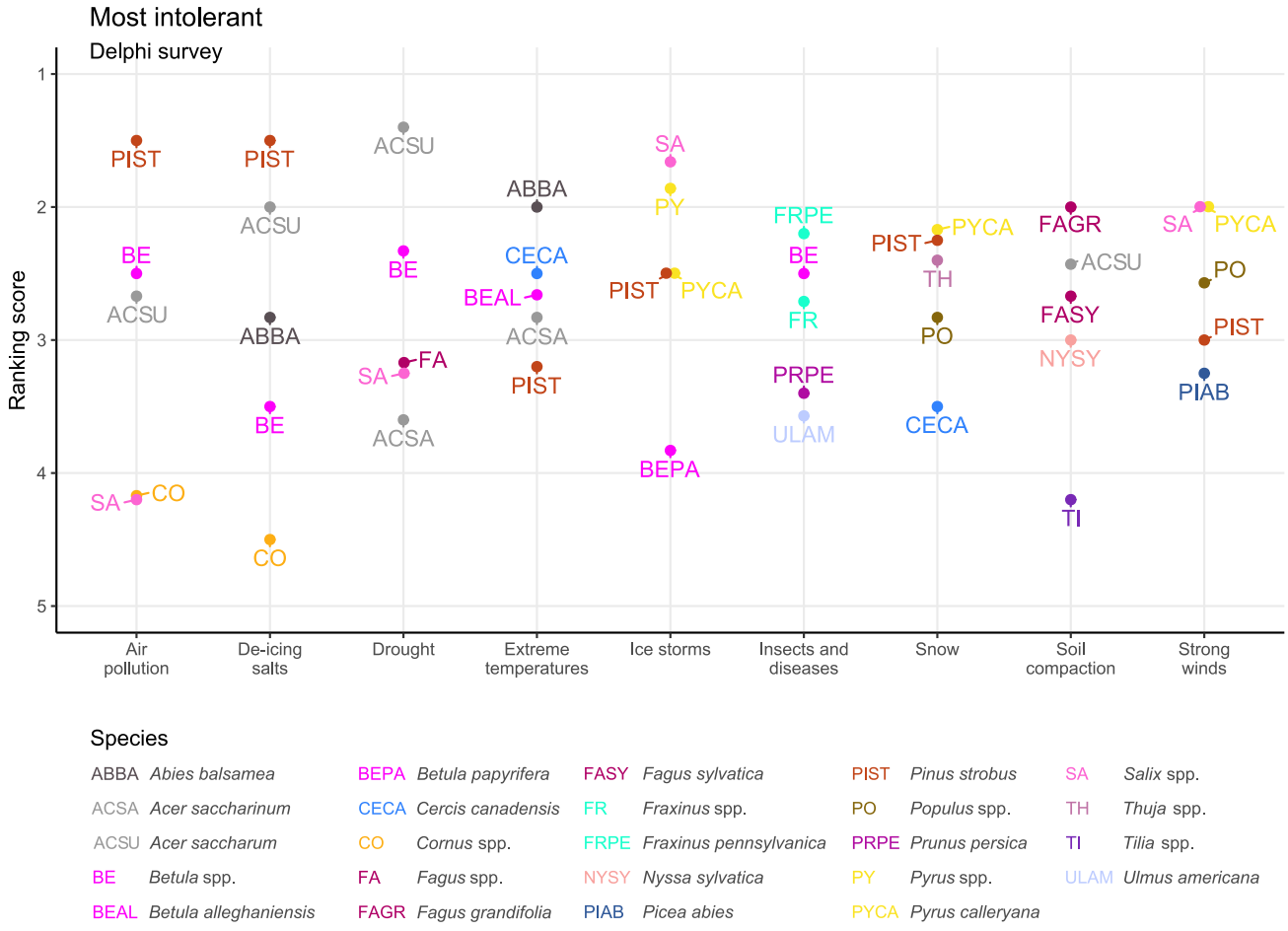

Figure 2. Ranking scores for the 5 species identified as the most intolerant to each studied stressor by the experts in the Delphi survey. The ranking score indicates agreement (or disagreement) with statements among experts (*n* = 7). The higher the ranking score, the higher the agreement regarding species intolerance. For instance, *Pinus strobus* was ranked first for air pollution with an average score of 1.5 on a scale of 1 (highest score) to 5 (lowest score), meaning that *P. strobus* was consensually regarded as intolerant to air pollution.

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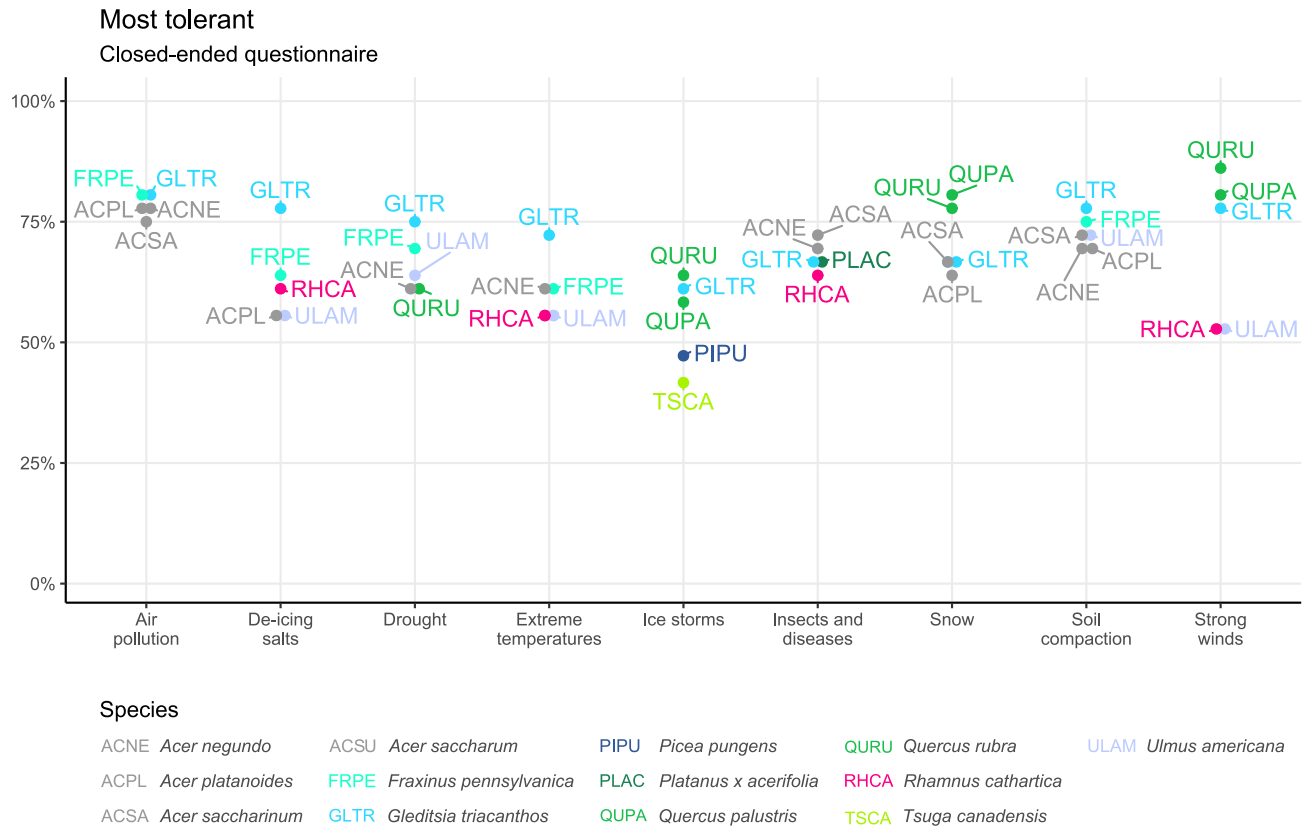

Figure 3. Most frequently mentioned urban tree species as tolerant or very tolerant to the studied stressors in the closed-ended questionnaire.

North America, the participants assessed *Acer negundo*, *Fraxinus pennsylvanica*, *Gleditsia triacanthos*, and *Ulmus americana* as the most tolerant to the different stressors (Figure 3). *Gleditsia triacanthos* was ranked as the most tolerant species to air pollution, soil compaction, drought, de-icing salts, and extreme temperatures; second for ice storms; and third for strong winds and snow. *Fraxinus pennsylvanica* was considered tolerant to air pollution, soil compaction, de-icing salts, drought, and extreme temperatures. *Acer negundo* and *U. americana* were identified as tolerant to soil compaction, drought, and extreme temperatures. *Acer negundo* was also selected as tolerant to air pollution and insects and diseases, while *U. americana* to de-icings salts and strong winds.

Knowledge Gaps

There are still some knowledge gaps to be filled regarding the effects of stressors. For instance, in the Delphi survey, the option "do not know" was chosen 13 times (out of 35) for snow and 10 times for ice storms, followed by de-icings salts and strong winds (7 times) and insects and diseases (6 times)(Figure 4). In the closed-ended questionnaire, the stressors with the lowest percentage of agreement regarding species' vulnerabilities were de-icing salts and extreme temperatures. While the stressors were the same in both surveys, the species put forward by the Delphi experts as tolerant or intolerant and those included in the closed-ended questionnaire were not identical.

DISCUSSION

The species most often mentioned as tolerant to several stressors was *Gleditsia triacanthos*, in both the Delphi and closed-ended questionnaires, which might be why it tends to be overused in urban landscapes. The experts also cited *Ginkgo biloba* as tolerant to several stressors, along with *Quercus* and *Ulmus* species. No species were rated as tolerant to all stressors. *Betula* spp. and *Pinus strobus* were the species most

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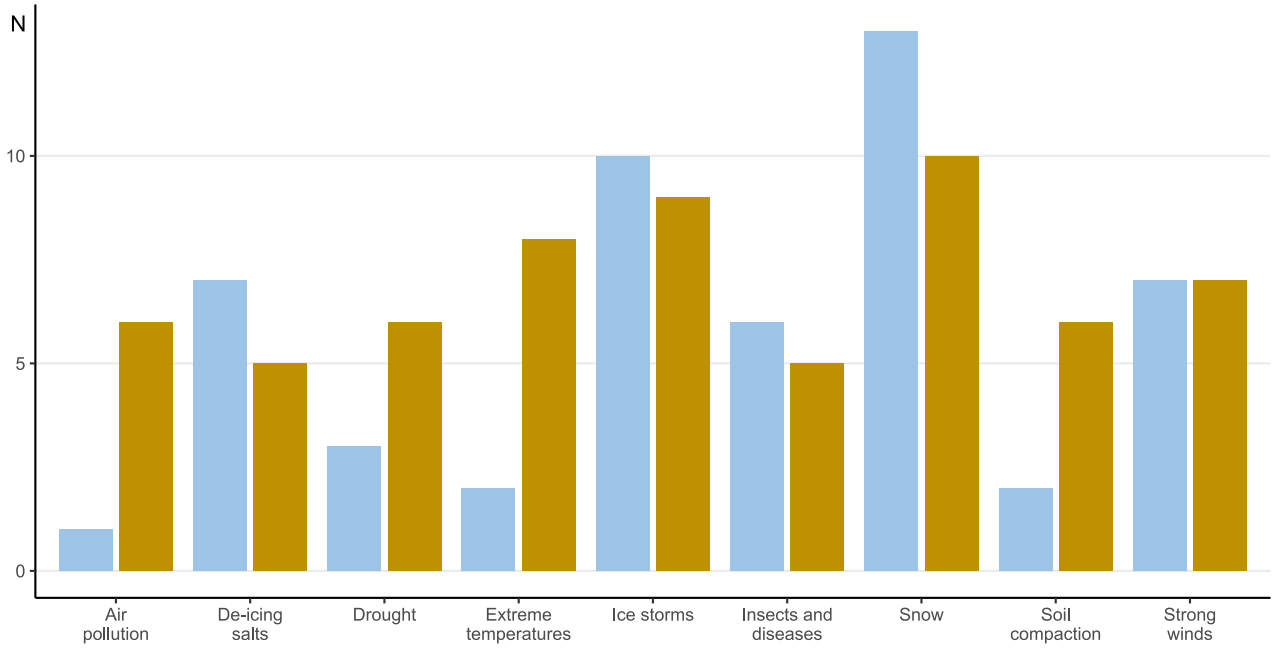

Figure 4. Number of times (*N*) the experts in the Delphi survey (*n* = 7) chose the "do-not-know" option and did not rate a given species as tolerant (blue) or intolerant (brown) for each stressor.

often selected as intolerant. We have also found that there are tree species that experts ranked as 'tolerant' and 'very tolerant' to urban stressors but are not among the most abundant urban tree species in cities in northeastern North America, such as *G. biloba* and *Quercus* spp.

Species-Specific Tolerances to Stressors

Ginkgo biloba, *Gleditsia triacanthos*, *Celtis occidentalis*, and *Ulmus* spp. were selected as the most tolerant tree species to air pollution. Pollutants, when absorbed by the leaves, may cause a reduction in the concentration of photosynthetic pigments, such as chlorophyll and carotenoids, which directly affects the photosynthetic apparatus and ultimately affects tree growth (Borsuk and Brodersen 2019; Locosselli et al. 2019). This would be consistent with the characteristics the Delphi participants identified as key to tolerance: thick leaves for the most tolerant trees and thin leaves for the most intolerant. It is also consistent with research on *G. biloba*, which is regarded as one of the most resistant species to air pollution and recommended in street plantings in areas where air pollution damages other species (Kim et al. 1997; Yang et al. 2014; Dmuchowski et al. 2019). The most intolerant species was *P. strobus*. Studies have shown that *P. strobus* trees have high air pollution removal efficiency but low tolerance to pollutants (Yang et al. 2014).

By decreasing soil porosity and therefore reducing the oxygen, water, and nutrient availability, soil compaction restricts root growth and development and may lead to poor tree growth in the long term and tree collapse in strong wind (Jim et al. 2018; Correa et al. 2019). *Gleditsia triacanthos* and *Ulmus* spp. were rated as tolerant to soil compaction in both questionnaires. Although the planting of *F. pennsylvanica* is not recommended, given its susceptibility to the emerald ash borer (Nowak et al. 2016), this species was also chosen among the most tolerant by the participants in the closed-ended questionnaire. *Acer saccharinum* and *A. negundo* were also listed in the closed-ended questionnaire as tolerant and they have been shown to be resistant to soil compaction (Day et al. 2000). According to the experts in the Delphi survey, being adapted to seasonal flooding was a trait that conferred tolerance to soil compaction. In wetlands, the soil is often waterlogged in the root zone, which decreases the oxygen available to roots. Therefore, species accustomed to waterlogged soils, and thus to hypoxia conditions, can also tolerate soil compaction. Experts also mentioned that being drought tolerant was important for tolerating soil compaction.

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Many studies have also stressed the impact of de-icing salts on urban trees. These salts, frequently used to de-ice roads and pavements in northern climates, can accumulate in the environment, affecting the uptake of water and nutrients by trees (Cunningham et al. 2008; Equiza et al. 2017; Ordóñez-Barona et al. 2018). High levels of salt in the soil reduces its water-holding capacity as well as retards soil-atmosphere gas exchanges, thus limiting root development and the ability of trees to grow (Ordóñez-Barona et al. 2018). In both questionnaires, *G. triacanthos* and *F. pennsylvanica* were listed as the species with the highest tolerance. This is consistent with research that shows that *G. triacanthos* blocks the uptake of chlorine (Cl) and sodium (Na) by the leaves, which accumulates in roots and shoots, suggesting a defense mechanism through the compartmentalization of these elements in the roots and may result in low sensitivity to salt stress (Dmuchowski et al. 2020). *Fraxinus pennsylvanica* has also been regarded as a relatively salt-tolerant tree for its ability to maintain low content of Na in leaves, either by restricting Na uptake or by reducing its transport to the leaves (Equiza et al. 2017). Almost all the species listed as tolerant to de-icing salts were also reported tolerant to soil compaction, the exception being *F. americana*. *Acer saccharum* was mentioned as intolerant in both surveys. *Pinus strobus*, *Abies balsamea*, and *Betula* spp. were also rated as intolerant by the Delphi experts.

As for insects and diseases, there was considerable divergence regarding the most tolerant species between the 2 questionnaires. According to the experts who participated in the Delphi survey, *G. biloba* and *G. dioicus* were identified as the most tolerant species. These results are consistent with previous research that has shown that both species are relatively resistant to insect and disease pests. *Ginkgo biloba* is largely free of insect pests due, at least partly, to the strong repelling effect conferred by its unique secondary metabolites (Pan et al. 2016). *Gymnocladus dioicus*, although less studied, has also been reported to be relatively free of insects and pests (Potter et al. 2019; Beckman et al. 2021). Unsurprisingly, *F. pennsylvanica* and *U. americana* were selected as intolerant. Once among the most common trees in urban areas across North America, the rapid spread and impact of the Dutch elm disease (on *Ulmus* spp.) and the emerald ash borer (on *Fraxinus* spp.) have caused widespread decline and mortality of these trees, and consequently, their planting is no longer recommended.

Extreme weather events are likely to increase in the future, which means that urban trees are going to be more exposed to strong winds, ice loads, heavy snow, and other winter hazards that can damage them (McPherson et al. 2018). Concerning the trees chosen as the most tolerant to wind, both in the Delphi and in the closed-ended surveys, trees from the genus *Quercus*, namely *Q. alba*, *Q. rubra*, and *Q. palustris*, were rated as tolerant to wind thrown. For strong winds, having a strong branch attachments (i.e., able to withstand high wind speeds), deep and stable rooting, and high wood density has been shown to have direct influence on a tree's ability to resist wind damage (Curran et al. 2008; McPherson et al. 2018). Pruning can also act as a preventive practice to protect trees from wind throw (Gilman et al. 2008). As for the species rated as the most intolerant, there was little agreement between the 2 questionnaires, but included *A. saccharinum*, *A. negundo*, *Fraxinus* spp., *P. strobus*, and *Picea abies*.

As for ice storms and their impacts, it depends on general tree characteristics such as coarse branching patterns, strong branch attachments, and lateral branches with reduced surface area, as well as on factors such as the amount and duration of accumulated ice, exposure to wind, and duration of the storm (Hauer et al. 2006). The tree characteristics of the most tolerant species upon which the experts agreed were dense wood, good structure, strong attachments, decay free, flexible branches, small crown, and slow growth. The species that were listed as most tolerant by the experts of the Delphi survey were species from the genus *Quercus*, *Juglans*, and *Gleditsia triacanthos*. This is consistent with previous studies on tree damage following ice storms in northeastern North America that suggested that *Juglans* species such as *J. nigra* tolerate winter temperatures without suffering damage and are strongly resistant to ice damage (Burban and Anderson 1996; Hauer et al. 2006; Guàrdia et al. 2013). By contrast, *G. triacanthos* has been cited as susceptible to ice damage (Burban and Anderson 1996; Hauer et al. 2006). Several species of the genus *Quercus* were also rated as tolerant in both questionnaires. By contrast, species of the genus *Salix* were named as most intolerant by the Delphi participants, followed by *B. papyrifera* and *P. strobus*. In the closed-ended questionnaire, *A. saccharinum* and *A. negundo* were among the most intolerant.

Snow damage can be caused by large amounts of snow accumulating on tree crowns, which can cause larger branches to break off or the entire crown from

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the weight of snow or ice. The experts in the Delphi survey pointed out that deciduous trees, in good health and condition, with dense wood and early leaf drop, were the most tolerant to snow damage. Deciduous trees often have more dense wood that can support heavier loads, and dropping their leaves before winter helps trees avoid the risks of snow or ice loading that can cause damage (Pearse and Karban 2013). *Quercus* spp. were consistently rated as the most resistant to snow damage in both questionnaires. The Delphi experts singled out *Q. alba* and *Q. rubra*, while the respondents in the closed-ended questionnaire named *Q. palustris* and *Q. rubra*. The other species that followed were *G. triacanthos*, *A. saccharum*, and *A. platanoides*, which are also hard-wooded species with a moderate to slow growth rate. *Pinus strobus*, previously rated susceptible to strong winds and ice storms, was also rated as intolerant to snow. In the closed-ended questionnaire, *A. saccharinum* was the species rated as more intolerant to snow damage. It is noteworthy that there was a general lack of agreement among the experts with regard to the most tolerant and intolerant species to snow damage (Figure 4). This suggests there is a lack of knowledge and a need for further research on how tree species respond to snow conditions (and ice storm disturbance).

The effects of drought and extreme temperatures are particularly related. Tree species with high drought and heat tolerances are likely to have greater suitability for urban areas since growing conditions are already today influenced by reduced water availability and higher temperatures in cities (Nitschke et al. 2017; Wang et al. 2019). The species listed as the most tolerant to drought were *G. biloba*, *Ulmus* spp., and *Celtis* spp. They were followed by *Q. macrocarpa*, *G. triacanthos*, and *G. dioicus*. Almost all of them were also selected as tolerant to soil compaction (*Ulmus* spp. and *G. triacanthos*) and de-icing salts (*Celtis* spp., *G. triacanthos*, and *G. dioicus*). This is in accordance with the experts' views on the characteristics that make trees tolerant to drought, such as tolerance to soil compaction and salt. As both drought and high levels of salt induce osmotic stress, cross-tolerance responses and mechanisms may occur (Leksungnoen 2012). Similarly, *A. saccharum* was rated as the most intolerant species in both questionnaires and it has also been chosen as intolerant to soil compaction and de-icing salts. Among the most common urban tree species that were not mentioned by the experts in the Delphi survey but were rated as tolerant in the closed-ended questionnaire were *F. americana* and *A. negundo*. The latter is recognized as a drought-tolerant tree species (Sjöman et al. 2015), but *F. americana* appeared to be sensitive to drought (Percival et al. 2006).

The impact of extreme temperatures, particularly high soil temperatures, can cause severe damage to the roots, resulting in a substantial reduction in shoot growth, which, in turn, can negatively affect tree growth and survival (Czaja et al. 2020). Extreme soil temperatures also influence soil moisture content, soil respiration, soil organic matter decomposition, and nutrient availability (Rustad et al. 2001; Czaja et al. 2020). Urban trees growing in paved areas, such as asphalt and concrete, are more prone to extreme temperature stress. Soil temperature can also generate stress conditions in the winter. *Gleditsia triacanthos* was chosen as tolerant to extreme temperatures in both questionnaires, as well as trees from the genus *Ulmus*. Having deep roots was mentioned in the answers to the Delphi survey as an important characteristic that confers resistance to this stress. In contrast, shade tolerance was mentioned as a characteristic of the tree species more intolerant to extreme temperatures. *Acer saccharum* was listed in the 2 questionnaires as the most intolerant species to extreme temperatures. However, some cultivars have been described as heat tolerant, highlighting the challenges in assessing a single species tolerance (Sjöman et al. 2015). The other species chosen as less tolerant to extreme temperatures was *Tsuga canadensis*.

Interaction of Stressors

The complexity of urban environments encompasses environmental and anthropogenic factors that can affect tree growth and vitality. With the Delphi survey, we saw that the participants have agreed on some of the effects that interactions between urban stressors may exacerbate, especially those occurring in winter, such as when wind, ice, and snow interact. Strong winds can increase the potential for damage from ice accumulation, for instance, when constant ice loading further stresses a weakened area in a branch (Hauer et al. 2006). Residual damage from ice storms, such as falling branches and trunks weakened by ice loading, can occur several months to years later (Hauer et al. 2006). Another winter stress that tends to happen in early spring and late autumn is wet snow. This type of

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snow is warm with high moisture content, making it easier to adhere to a stem in strong winds, unlike dry snow. Hence, it can add a lot of weight to the tree, which, if not structurally stable, can eventually break (Nykänen et al. 1997). Experts also agreed that the effects on urban tree species are aggravated when soil compaction interacts with de-icing salts and drought. In addition to species-specific characteristics and tolerances to salt and drought stress, physical characteristics of the soil, such as the level of compaction and soil texture, have also been found to influence the amount of salts that accumulate in the soil (Ordóñez-Barona et al. 2018) and the availability of water (Scalenghe and Ajmone-Marsan 2009). Another interaction that participants highlighted was drought with diseases. This is consistent with a previous study that found that urban warming can directly increase pest fitness and abundance in urban forests (Dale and Frank 2017), providing further evidence that drivers of pest insect outbreaks act in concert rather than independently. Extreme temperatures and drought were the last interaction cited. With climate change, extreme temperatures and drought will happen more frequently (IPCC 2022), likely affecting urban tree growth. This is supported by observations from previous studies that have shown that urban warming was associated with reduced growth of urban trees and that water stress both reduces tree growth on its own and exacerbates the effects of warming and insect pests on tree growth (Meineke et al. 2016; Nitschke et al. 2017; Meineke and Frank 2018). Still, there is a lack of information about the effects that multiple potential stressors may have when they occur at the same time, as they often do. Only some studies have tried to address this problem, and a considerable gap exists around the combined effects of these interactions in urban forests (Steenberg et al. 2017; Meineke and Frank 2018).

Management Implications

The temporal scale of environmental stressors affecting trees in urban areas is particularly important with regard to which selection criteria to look for and when and which management actions are required to ensure longer life spans of the trees in the urban areas (Sæbø et al. 2003; Ossola et al. 2021). However, despite the ever-increasing body of research on species' responses to individual stressors (e.g., Sæbø et al. 2003; Roloff et al. 2009; Yang et al. 2014; Sjöman et al. 2015; Vogt et al. 2017; Dmuchowski et al. 2020), many challenges remain. For instance, in order to implement efficient management practices, it is necessary to improve our understanding of the mechanisms underpinning stressor interactions, how tolerant species are to multiple stressors, as well as adapt management programs in light of new evidence on the short- and long-term effect of these multiple stressors, alone and in combination, on the biological responses of urban trees (Vinebrooke et al. 2004; Harris et al. 2018; Ossola et al. 2021). In our study, although we did not explicitly ask respondents about the time scale of tree species' responses to the studied stressors, our findings add support to the importance of considering the complex interactions between stressors and how that can ultimately impact urban trees.

Another aspect relevant for management is how introduced species are managed. While some non-native trees may be more tolerant of certain urban stressors and, as a result, survive and grow better, their invasive potential risks are not negligible (Gaertner et al. 2016). This is, for instance, the case of *A. platanoides*, which, although not native to North America, has become invasive in forest understoreys near cities (Bertin et al. 2005; Martin and Marks 2006; Wangen and Webster 2006; CABI 2019). Unlike many invasive species, *A. platanoides* is still widely planted as an ornamental in cities throughout Europe and North America due to its ability to tolerate urban conditions (Bertin et al. 2005; CABI 2019), which is consistent with our findings. Respondents regarded *A. platanoides* as tolerant to air pollution, de-icing salts, drought, and—in both surveys—compacted soils. Underestimating the invasive potential of many common ornamentals is one of the greatest risks in urban forest management, but exploring the complexities of managing non-native species in cities was not within the scope of our study.

Study Limitations and Future Directions

Growing trees in cities is about more than just species selection. Even carefully selected tree species must be cared for if they are to survive and thrive (Sousa-Silva et al. 2023), but choosing the right species can improve tree survival and growth and save money in the long run through lower maintenance and replacement costs. Our findings can inform the decisions made by those engaged in planting and managing trees, especially in the Northeastern United States and

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Eastern Canada. Yet, the transferability of our findings to other geographic areas should account for the potential invasiveness of these species, which we did not cover in our study, as well as for other stress factors and growth requirements. Nevertheless, our approach can be readily adapted and replicated in other regions where different species may be exposed to different types of stressors. We also encourage future research to test the degree and rate by which urban tree species respond to stressors (e.g., the onset of water scarcity and the emergence of observable consequences on trees) and how the time scale of the response could underpin effective urban planning and management interventions. More research efforts could also be directed toward small-scale local studies of species-specific responses to multiple stressors whose impact may differ by location (Sjöman and Nielsen 2010; Conway and Vander Vecht 2015). This will provide critical information to guide future management recommendations.

Our results belong to a "context of discovery" rather than a "context of justification" (Perla and Carifio 2009). The Delphi methodology assumes that the respondents are experts with a high level of knowledge about the subject studied and are accurate in their answers and comments. This was the case in our study as the experts who participated had more than 10 years of working experience as urban forestry professionals in cities across the Northeastern United States and Eastern Canada. Therefore, they are assumed to be knowledgeable professionals with sufficient expertise and experience with trees in the site conditions of the targeted region, which makes their responses, and by extension, our results, particularly useful and valuable. The main limitation of this study is that the total number of participants who made it to the third round of the survey was only 7, which is just below the 10 minimum (Okoli and Pawlowski 2004). This may imply not having a representative sample of the targeted people, resulting in low response reliability.

Also, a definition of tolerance was not provided in the surveys and was open to respondent interpretation. Therefore, all results are based on one's own definition, which in retrospect could have led to inconsistent responses. We do not know if all participants shared a common interpretation of the word tolerance, since we did not give a specific definition. Yet, as this research was undertaken from a rather exploratory point of view, this is unlikely to have greatly affected the results.

CONCLUSIONS

This study is another step forward in our quest to better understand tolerance of trees to the different stressors in urban settings. The information gathered from the 2 surveys targeting 2 different populations has allowed us to fill some gaps in our knowledge of the tolerance (and intolerance) of common urban tree species to urban stressors and identify others that remain unaddressed. Specifically, our results pointed out that there is consensus among experts that all species have some ability to cope with stressors, but that tolerance is highly complex, and no species is tolerant to all stressors. We encourage future research to test additional assumptions and conduct empirical experiments on species-specific vulnerability to stressors. Until more knowledge is available, steps could be taken to favour urban tree species that are resilient and adaptable to a broad panoply of stressors, as well as enhance tree species diversity. Using suitable tree species for urban conditions will ensure maximum benefits and help reduce the costs associated with replacing trees while building the resilient urban forests the 21st-century needs.

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Appendix.

The Delphi process was structured into 3 rounds. The responses from the first round were analyzed using content analysis, a well-established data analysis method to organize large amounts of text into categories that reflect a shared meaning (Kleinheksel et al. 2020). The content analysis was done manually and consisted of reading and rereading the responses, developing a process of coding, categorizing, and summarizing the answers (Hsieh and Shannon 2005). A total of 9 categories emerged from the first round of open coding as presented in Table S1. These categories, regarding the characteristics of trees related to their tolerance and intolerance to each stressor, were more or less consistent across stressors. Still, they also included statements/categories that did not describe tree characteristics, such as good growth or form, but environmental factors like temperature and soil conditions. These categories were omitted from the second round. A total of 152 statements formed the basis of the second questionnaire. Then, in the second and third rounds of the survey, the experts were asked to rate the statements through a 5-point Likert scale, and they could revise and clarify their earlier answers if they chose to do so. After each round, statements for which 75% of the participants answered that they agreed or strongly agreed with that statement were retained and aggregated in Table S2.

Table S1. Categories that emerged from the responses from the first round to the question about urban tree species characteristics related to their tolerances to urban stressors.

Categories (examples)	Retained/omitted in subsequent round
Climate (e.g., summer heat)	Omitted
Tree management (e.g., pruning)	Omitted
Site conditions (e.g., soil)	Omitted
Origin (native or non-native)	Retained
Growth strategies (fast vs. slow growth)	Retained
Leaves (e.g., leaf form, shape, surface characteristics)	Retained
Roots (e.g., deep vs. shallow root systems)	Retained
Other (e.g., health status)	Retained

Table S2. Characteristics of the most stressors-tolerant and stressors-intolerant trees as indicated by the participants in the Delphi survey.

	Tolerant	Intolerant
Air pollution	Good health, thick leaves	Thin leaves
De-icing salts	Waxy leaves, tolerance to soil compaction and drought	Conifers, shallow roots, thin bark, require moist and well-drained soils, planted without protection or protocol
Drought	Soil-compaction tolerance, deep roots, waxy cuticles, good health, native species from drought-stressed places, salt tolerance, good water-storage capacity	Shallow roots
Extreme temperatures	Deep roots, waxy surfaces, leaf pubescence, regulation of water loss, old age	Shade tolerance
Ice storms	Dense wood, good structure, strong attachments, decay free, flexible branches	Poor structure, narrow branch unions, evergreen, bark inclusions (or "ingrown" bark), weak wood, fast growth, wide crown
Insects and diseases	Good health, adaptation to different environmental conditions	*No agreement*
Snow	Deciduous, dense wood, good health, decay free, early defoliation, flexibility in the limbs, good structure	Deciduous, poor structure, weak attachments, weak wood, late defoliation, wide branches, fast growth
Soil compaction	Seasonal-flooding tolerance, drought tolerance, hard wood, native species from wetland sites	Drought intolerance, slow growth
Strong winds	Good structure, deep roots, stable rooting, slow growth, dense wood, good health	Poor structure, shallow roots, dense crown, weak roots, fast growth

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Background information of the participants in the closed-ended questionnaire.

Table S3. Education level of the participants in the closed-ended questionnaire.

Level of study (degree)	Number of participants
Doctorate	4
Master's	14
Bachelor's	13
Professional or Associate's	5

Table S4. Job titles of the participants in the closed-ended questionnaire.

Job title	Number of participants
Researcher	8
Arborist	9
Technician in arboriculture and horticulture	3
Professional educator	2
Director, deputy director in Forestry & Parks Department	4
Agent at NRCS, NRCan	3
Landscape architect	1
Did not answer	6

Table S5. Years of working experience of the participants in the closed-ended questionnaire in arboriculture and urban forestry.

Number of years	Number of participants
1-5	8
6-10	4
11-15	1
16-20	3
20-25	3
> 25	14
Did not answer	3

Regarding their job/city experience, the participants in the closed-ended questionnaire have studied or worked in cities across the following Canadian provinces and US states: Ontario (CA), New Brunswick (CA), Québec (CA), California (USA), Colorado (USA), Connecticut (USA), Florida (USA), Illinois (USA), Kentucky (USA), Maine (USA), Maryland (USA), Massachusetts (USA), Michigan (USA), Minnesota (USA), Missouri (USA), New Jersey (USA), New York (USA), North Carolina (USA), Ohio (USA), Pennsylvania (USA), Rhode Island (USA), Texas (USA), Virginia (USA), and Washington (USA).

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