Assessing climate risk to support urban forests in a changing climate

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Assessing climate risk to support urban forests in a changing climate

Summary

The management of urban forests is a key element of resilience planning in cities across the globe. Urban forests provide ecosystem services as well as other nature-based solutions to 4.2 billion people living in cities. However, to continue to do so effectively, urban forests need to be able to thrive in an increasingly changing climate. Trees in cities are vulnerable to extreme heat and drought events, which are predicted to increase in frequency and severity under climate change. Knowledge of species' vulnerability to climate change, therefore, is crucial to ensure provision of desired ecosystem benefits, improve species selection, maintain tree growth and reduce tree mortality, dieback and stress in urban forests. Yet, systematic assessments of causes of tree dieback and mortality in urban environments are rare. We reviewed the state of knowledge of tree mortality in urban forests globally, finding very few frameworks that enable detection of climate change impacts on urban forests and no long-term studies assessing climate change as a direct driver of urban tree dieback and mortality. The effects of climate change on urban forests remain poorly understood and quantified, constraining the ability of governments to incorporate climate change resilience into urban forestry planning.

Key words: tree failure; tree mortality; urban sustainability; urban planning; urban trees

Societal Impact Statement

Globally, cities are planning for resilience through urban greening as governments understand the importance of urban forests in improving quality of life and mitigating climate change. Urban trees provide ecosystem benefits to 4.2 billion people living in cities. Yet, the continuation of benefits requires urban forests to be resilient to climate change. Knowledge of species' climate vulnerability is crucial to ensure provision of ecosystem services, improve species selection and reduce tree mortality. Yet, systematic assessments of causes of tree dieback and mortality in urban environments are rare. The effects of climate change on urban forests remain poorly understood and inadequately quantified, constraining the ability of governments to incorporate climate change resilience into urban forestry planning.

1. Introduction

More than 4.2 billion people live in urban areas, which represent ~3 percent of the Earth's land area (Liu et al., 2014). As the human population grows, cities around the globe will continue to expand, increasing demand for food and services (FAO, 2010; UN, 2017). Within cities, urban forests comprise trees, shrubs and associated vegetation in a city, including street, residential and park trees, woodland and green belt vegetation (Miller et al., 2015). These forests provide numerous ecosystem services and benefits, such as heat mitigation, reduced stormwater runoff, biodiversity conservation and improvement of human health (Keeler et al., 2019). Urban forests, in both public and private spaces, can also help to mitigate the adverse impacts of global climate change by absorbing greenhouse gases and storing carbon (Bastin et al., 2019; Cimburova & Pont, 2021). Both heat mitigation and carbon storage in urban forests can contribute to meeting the target of limiting the rise in global temperature to 1.5 °C above pre-industrial levels (IPCC, 2018). However, to ensure the provision of these services as well as other nature-based solutions, cities require healthy, functioning urban forests.

Climate change — i.e. any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2014) — is a potential stressor affecting the performance and persistence of urban forests (Ordóñez & Duinker, 2014; Brandt et al., 2016; Esperon-Rodriguez et al., 2021a). A global assessment showed that > 50% of all plant species present in urban forests are exceeding their current climatic tolerance for mean annual temperature and, by 2050, this number will increase, jeopardizing the performance of urban ecosystems (Esperon-Rodriguez et al., 2021a). Climate change also increases the frequency and severity of extreme weather events, such as heatwaves, severe droughts and floods, which also threaten urban forests (Meehl & Tebaldi, 2004; Staudhammer et al., 2011; Yan & Yang, 2018; Zscheischler et al., 2018; Hilbert et al., 2019). These extreme events contribute to widespread dieback and increased tree mortality (Roman et al., 2014; Escobedo et al., 2016; Smith et al., 2019) (**Figure 1**). Therefore, it is reasonable to assume that ongoing anthropogenic climate change will play a key role in determining species' survival and the future composition of urban forests.

Urban forests are complex ecosystems and are typically stewarded and managed by people. Management activities, such as providing supplemental irrigation, may mitigate some of the negative effects of climate stress (Van der Veken et al., 2008). Urban forests not only experience extreme weather events, but some also face harsh conditions, such as growing in situations with limited soil volume and nutrients, soil compaction and extremes of soil moisture availability, as well as exposure to de-icing salt in cold climates, which can cause severe damage and reduced vitality of urban trees (Day & Bassuk, 1994; Gregory et al., 2006; Mullaney et al., 2015). Therefore, determining the direct drivers of urban tree dieback and mortality is challenging but essential in urban forestry planning to reduce environmental and socio-economic losses associated with failures and mortality, and to ensure sustained provision of ecosystem services by urban forests (Cimburova & Pont, 2021).

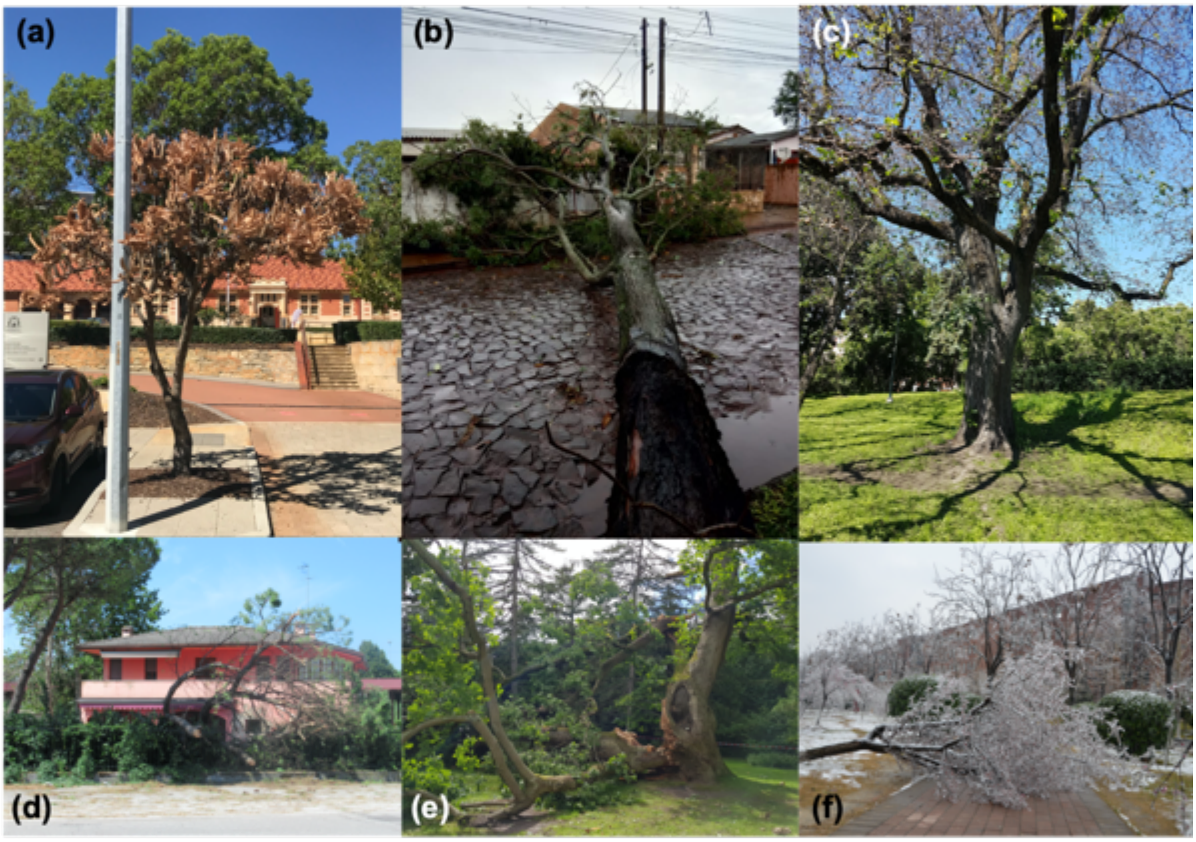

Figure 1. Examples of urban tree mortality and dieback as a result of extreme weather events across the globe: (a) Banksia spp. dieback after an extreme heat and drought event in Perth, Australia; (b) tree uprooted by wind and storm in Foz do Iguaçu, Brazil; (c) Ulmus sp. affected by a long drought period in Oslo, Norway; (d) tree damage associated with a cyclone in Padua, Italy; (e) storm damage to an oak tree in Alnarp, Sweden; and (f) tree collapse resulting from ice formation in the tree canopy in Nanchang, China. Photos provided by the authors in order MER, AAE, IS, AR, JÖ and JY.

In general, tree dieback and mortality often result from a slow accumulation of the effects of many stresses through time and interactions among multiple factors, including human removals of diseased and declining city trees prior to mortality (Franklin et al., 1987; Hilbert et al., 2019; Czaja et al., 2020; Hauer et al., 2020a; Hauer et al., 2020b).

Management decisions along the way can either exacerbate or ameliorate risks associated with tree dieback and mortality (**Figure 2**). Both human activities (i.e. management) and biophysical factors can be contributing causes of mortality (Hilbert et al., 2019). Inadequate management may include unsuitable plant or site selection, poor quality of nursery planting stock, inappropriate planting technique, insufficient site preparation and maintenance during the establishment period, construction (e.g. new development and redevelopment), and vandalism (van Doorn & McPherson, 2018; Hilbert et al., 2019; Hauer et al., 2020a; Hauer et al., 2020b). Biophysical factors include climate, extreme weather events, pests and diseases, herbivory, and browsing (Hilbert et al., 2019; Hauer et al., 2020a; Hauer et al., 2020b). Ultimately, management and biophysical factors are strongly interrelated because management actions often involve alteration of biophysical factors, such as soil structure, water and nutrient availability (Hilbert et al., 2019).

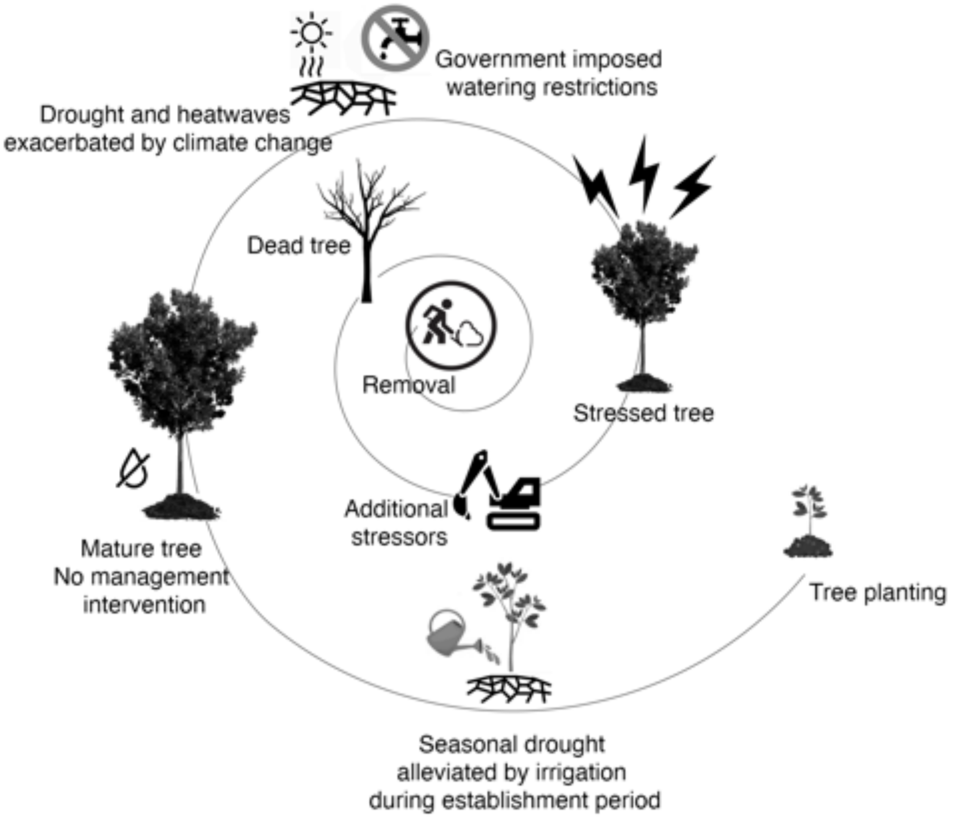

Figure 2. An example of the tree mortality spiral of urban tree failure and associated biophysical factors and management (adapted from Manion, 1981; Franklin et al., 1987; Hilbert et al., 2019).

Systematic assessments of the proximate causes of tree dieback and mortality in urban environments are rare, especially those assessing climate change as a direct driver of urban tree mortality. Therefore, the aims of this study were to (1) highlight the importance of climate change as a driver of tree mortality, (2) review the state of knowledge of tree mortality in urban forests globally, targeting studies reporting climate change drivers of urban tree mortality, and (3) propose recommendations to identify climate change-driven failures and prevention of urban tree mortality.

2. Climate change as a driver of urban tree mortality

Urban forests are vulnerable to changes in climate and extreme weather events, with some species being more vulnerable than others. Thus, incorporating the role of climate change as a driver of urban tree dieback and mortality and decline into management practices can help policymakers and urban forest managers reduce risks and economic losses. However, to date, this topic remains understudied.

Urban forests are affected by gradual or ongoing events, such as changes in climate parameters (e.g. rising temperatures, changing precipitation patterns), and by pulse or rapid one-off events (e.g. storms). Gradual events are less studied and research on climate change-driven mortality —i.e. long-term climate change impacts on urban tree inventory dynamics —are rare. In contrast, pulse events seem easier to research —measure before and right after, allowing attribution of response to the specific event. In some cases, extreme weather events can be recognized as drivers of mortality. A review of 120 cities in China, for example, associated extreme temperatures and storms with increased tree mortality (Yan & Yang, 2018). Similarly, in Sweden and Norway, extreme weather events, such as low temperature extremes and heavy snow, have been identified as causes of tree mortality (e.g. Pedersen & Brun, 2013; Sjöman & Slagstedt, 2015). Indeed, mortality may be linked to weather conditions during or after planting, but because planting failures may occur frequently, they are not necessarily attributed to climate events or climate change. Furthermore, these studies lacked the long-term data required to detect or attribute responses to climate change. In contrast, a study in Santiago, Chile, distinguished some effects of climate and management on tree mortality using data over a 12-year-period (2002-2014) and concluded that tree mortality was more influenced by improper management (i.e. poor species and site choice) than climate alone (Escobedo et al., 2016).

To date, however, there is a paucity of long-term monitoring studies in urban forests (see details about our literature search in **Supplemental Material**). We highlight this gap in knowledge and argue that effective urban forestry is only possible by including climate change in all its guises (e.g. extreme weather events, shifts in precipitation and temperature patterns) as a potential driver of tree mortality, crown dieback, visible injury, defoliation and poor growth, as well as secondary impacts from climate change-induced increases in pests and diseases (Linnakoski et al., 2019). As climate changes, it will become difficult to mitigate the effects of excessive heat or drought through management actions such as irrigation, to offset soil water deficits, particularly in regions with limited urban water supply (Pataki et al., 2013; Roman et al., 2014). Furthermore, there are few cost-effective management options available for mitigating rising air temperatures. The long-term sustainability of urban forests, therefore, depends on the identification of species and cultivars that will continue to be suitable in a given location under climate change (McPherson et al., 2018).

Identifying species and genotypes likely to be tolerant of future climates is an option for expanding the current palette of tree species within different locales (e.g. Yang, 2009; Brandt et al., 2017; Steenberg et al., 2017; McPherson et al., 2018; Burley et al., 2019; Esperon-Rodriguez et al., 2019; Sadeghabadi et al., 2020). Initiatives such as Citree database (Vogt et al., 2017) in Germany, the Vermont Tree Selection tool (<https://vtcommunityforestry.org/resources/tree-care/tree-selection>) and Tree Species Selection Guide from the Tree Research and Education Endowment Fund (<https://treefund.org/archives/15983>) in the USA, and the Which Plant Where program (<www.whichplantwhere.com.au>) in Australia, provide science-based evidence on species' tolerance to inform species selection. In Iran, a recently developed tree failure model (TFM_{mlp} tool) provides an environmental decision support system using artificial intelligence to identify trees at risk of extreme weather (e.g. wind storm) in forest lands (Jahani & Saffariha, 2021). Published studies also provide valuable information on species' tolerance and climatic limits in urban settings (e.g. Yang, 2009; Brune, 2016; McBride & Laćan, 2018; Burley et al., 2019; Esperon-Rodriguez et al., 2019; Smith et al., 2019; Esperon-Rodriguez et al., 2021a). Such studies provide details on species' climatic thresholds based on their known distributions (i.e. realized climatic niches). Metrics of tree species' climate envelopes (e.g. growing degree days) or tolerance of cold (e.g. hardiness zones) can be used to inform species selection in a changing climate. For these metrics to be useful, however, they must be available to policymakers, governments and nursery growers to make informed decisions in relation to future climate.

To date, nursery growers mainly base species decisions on field trials to assign cultivars to particular hardiness zones or classes, but this approach is based on past and current climate and does not account for future climate change. Additionally, growers need research on species' climatic tolerances to inform species choice and educate consumers.

Thus, we must consider the possibility that rapid climate change may result in time lags between the identification and production of suitable species in nurseries, changing local climatic conditions at planting, and climatic conditions over the lifespan of an individual tree. Given the comparatively slow growth rates of trees and the importance of promoting tree longevity, new species selections must be planned years and decades in advance.

Information and knowledge on climate-sensitive species are embedded in the practice of arboriculture and urban forestry, but is often not clearly collated or accessible. Where available, reports in the grey literature are often anecdotal, restricted in scale, and frequently limited in scope in terms of numbers of species or sites, constraining their usefulness or broad applicability. For many cities around the globe, local governments (e.g. councils and municipalities) do not keep tree inventories, let alone accurately or consistently record mortality rates of new tree plantings or established trees (van Doorn et al., 2020). Dynamic inventories are costly, and thus, financial limitations make monitoring and collecting data extremely challenging and may perpetuate the lack of information (Ramage et al., 2013; Roman et al., 2013). Remote sensing data with individual tree canopy resolution does, however, offer a cost-effective approach to account for long-term changes in urban tree canopy cover (Hanssen et al., 2021), even though information on individual tree species performance may be missing.

3. Recommendations to identify climate change-driven failures and prevent urban tree mortality

Here, we identify the information and tools needed to detect and attribute climate change as a direct driver of tree dieback and mortality in urban forests. We found two key components missing in the literature: (1) long-term monitoring studies assessing urban tree mortality caused by changes in climate; and (2) studies on urban tree mortality caused by extreme weather events linked to climate change. Further, there is a need to incorporate climate change as a potential driver of mortality in urban tree inventories via long-term monitoring assessments. These needs arise for three main reasons. First, researchers and resource managers have yet to undertake sufficient studies of the role of climate change as a driver of tree mortality in urban forests. Second, the climate change signal, when present, can be overwhelmed by the noise of other mortality drivers. Finally, acute climate change impacts are dispersed in space and time, complicating attribution of antecedent climate events to observed urban tree mortality.

3.1. The role of climate change as a driver of tree mortality in urban forests

To disentangle the effects of climate change on urban forests, we recommend conducting long-term monitoring of urban forests that incorporates detailed data on growth and mortality into urban tree inventories. Also, taking a demography approach (van Doorn & McPherson, 2018), which would entail growth, removals (incorporates mortality but recognizes that sometimes trees are cut down when still alive) and plantings or recruitment. These data will aid in identifying successes and failures of plantings within urban settings and help develop tree management plans for climate resilience (Venter et al., 2020).

We emphasise the need of implementing easy, systematic and long-term methods for collecting urban tree inventory data that document potential causes of mortality and identifies risks associated with every stage of urban tree growth and development (Hauer et al., 2020a; Hauer et al., 2020b; Roman et al., 2020; van Doorn et al., 2020). Tree mortality can be used as a metric of success in planting programs (Roman et al., 2013). Systematic data collection and monitoring should be longitudinal, tracking individual trees over time in surveys undertaken annually (during the establishment period, e.g. < 5 years) or every five years (for established, mature trees, e.g. > 5 years) to assess tree growth and health and evaluate specific risks or threats such as diseases and pests. Regular data collection should include size metrics of tree height (trunk and crown) and stem diameter, tree health assessments, along with symptoms of stress (e.g. diseases, pests, heat stress assessed though leaf damage; Esperon-Rodriguez et al., 2021b). This last metric is very important, as climate change can affect tree performance without killing them; these effects go largely undetected in urban tree inventories.

Measuring plant traits and attributes, such as bud burst, flowering and leaf colour, can be useful in evaluating climate-driven change in plant phenology, performance and damage. Additionally, conducting experimental trials and studies of plant functional traits can provide more detailed information about species' performance and tolerance in urban environments (Esperon-Rodriguez et al., 2020; Hirons et al., 2021). Unfortunately, the current lack of such data increases uncertainty around decision-making for future urban forests.

Establishing standardized physiological tolerance metrics (e.g. leaf turgor loss point, leaf critical temperature for photosynthesis or proline content), and developing national and international inventory and assessment protocols along with urban tree mortality and growth databases can provide the means to identify vulnerable and resilient species and relate these to particular climatic conditions over the widest possible geographic areas. Selection of resilient species, therefore, should be also based on life history and physiological information. Global and regional plant trait databases, such as TRY, AusTraits databases for Australia and BROT 2.0 for the Mediterranean Basin (Tavşanoğlu & Pausas, 2018; Kattge et al., 2020; Falster et al., 2021) can provide information on life-history and physiological traits relevant to climatic tolerances.

Field data collection protocols and quantitative guidelines based on successful existing inventories can be used to standardize data collection (McPherson et al., 2016; Roman et al., 2020). In addition to ground-based inventories, we recommend using remote sensing of urban tree cover (Hanssen et al., 2021). Monitoring protocols should capture the role of climate change and allow for data collection at regular intervals (i.e. dynamic inventories) in relation to extreme weather events. Incorporating climate trends assessments (e.g. meteorological data of trends in mean winter low temperatures, summer high temperatures, growing season precipitation) into long-term monitoring can help to identify species' responses to altered temperature and precipitation regimes and test links between the role of climatic factors and failure rates. The US Long-Term Ecological Research Network is an example of how this type of research can be conducted to address questions on forest resilience in non-urban settings (Mirtl et al., 2018).

Monitoring also should be conducted during and after periods of acute climate stress and incorporate new plantings with regular monitoring to record change of status in terms of tree health, tree mortality or damage arising from vandalism or other factors. Data collection could also integrate tree removal and planting permits into inventories, to make "living inventories" instead of "static inventories", and incorporate community monitoring to capture less severe climate impacts and include information about dieback and tree failures detected by the community that do not necessarily require tree removal. The program "Become a Citizen Forester" from the City of Melbourne, Australia, aims to provide tools for citizens to help creating resilient, healthy and diverse urban landscapes. The web tool to visualise Melbourne's urban forest has the option to locate individual trees and send emails directing concerns or updates for each tree (<melbourneurbanforestvisual.com.au>). Also, California USA's "Climate ready trees" is a multi-partner study evaluating the ability of promising but underused trees to tolerate changing climates (McPherson et al., 2018). These types of initiatives can provide insights into how the community can participate in identifying failures and tree mortality as well as in selecting appropriate species.

Finally, we recommend developing species-level indicators that are observable and verifiable, quantitative or qualitative, relevant to local decision-making, specific and measurable, dynamic (i.e. change over relatively short time periods) and that rely on available data (Tyler, 1996). When data on species' tolerances are available, these can be used to compare vulnerability among species and identify those at most risk. We recommend using the species' thermal safety margin (i.e. the difference between body [e.g. leaf] temperature and the temperature at which loss of function occurs [thermal tolerance]). The thermal safety margin is recognized as a good indicator of species' vulnerability to climate change and their physiological capacity to cope and thrive under critical temperatures (Clusella-Trullas et al., 2021). In cases where data on species' tolerance are not available, we suggest using data from urban tree inventories (e.g. number of trees, growth and mortality rates) to achieve this goal (**Box 1**).

***Box 1**. We propose three approaches to identify climate change-driven failures and prevent urban tree mortality. (1) **Thermal Safety Margin**. Using data on species' climatic tolerance, the thermal safety margin (S) can be calculated. This metric indicates how much warmer (or drier), a city could become before the realised climate niche of its species will be exceeded (Esperon-Rodriguez et al., 2019; Gallagher et al., 2019; Esperon-Rodriguez et al., 2021a) and is calculated as the difference between the species' climatic limit for a given climatic variable and the climate conditions of the city where the species is planted (**Figure 3**). (2) **Vulnerability Index**. When data on species' tolerance are not available, a vulnerability index may be calculated using three components: the number of individuals for a given species; growth rate for a given period; and mortality rate for that period. A species is considered to be more vulnerable with a lower number of individuals, lower growth rates and high mortality rates than other species in a particular urban forest inventory. (3) **Integration of Thermal Safety Margin and Vulnerability**. When available, integration of species' tolerance into the vulnerability index by adding the species' thermal safety margin for climate (**Figure 4**). See details of the estimation of these metrics and examples in **Supplemental Material**.*

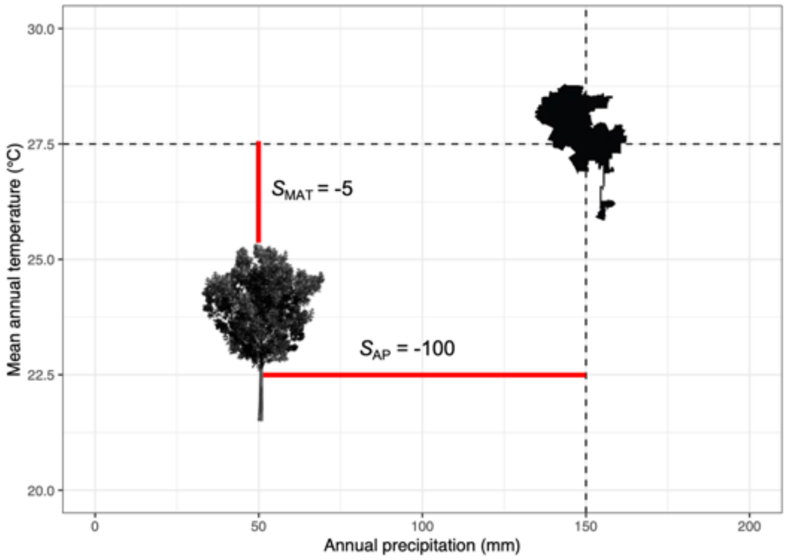

Figure 3. Example of the estimation of a tree species' thermal safety margin for mean annual temperature (S_{MAT}) and annual precipitation (S_{AP}) planted in a given city. For example, a city with a mean annual temperature (MAT) of 27.5°C and annual precipitation (AP) of 150 mm, has a species with a realised climate limit of 22.5°C and 50 mm for MAT and AP, respectively. Here, the species is currently experiencing unsafe conditions for MAT, as the city climate (i.e. MAT = 27.5°C) is 5°C warmer than the species' limit (MAT = 22.5°C); whereas for precipitation, the species is experiencing safe conditions, as the species' limit (AP = 50 mm) is lower than the city's threshold (AP = 150 mm). This metric can help to identify species at most risk of climate stress.

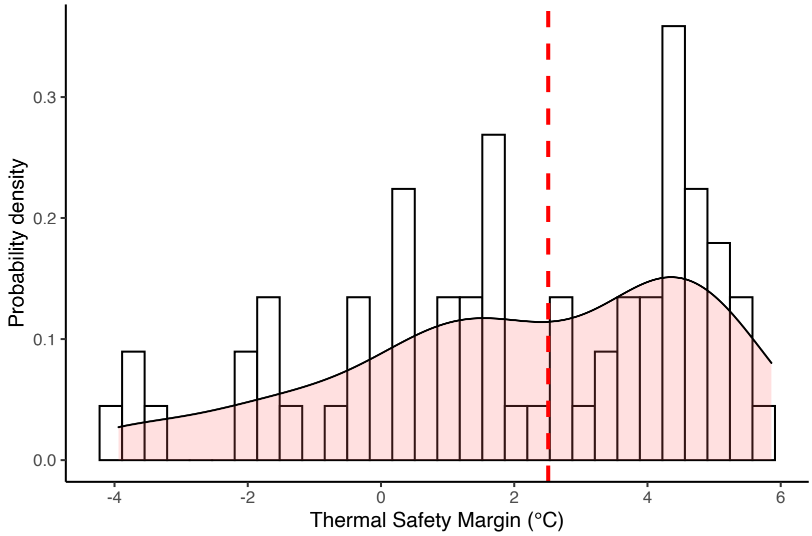

Figure 4. Probability density of the thermal safety margin for 66 urban tree species in Sydney Australia using data for mean annual temperature of the species climate niche. Shaded area indicates the data distribution and the red dashed line indicates the data median. Species approaching or falling below zero are considered at climate risk.

3.2. Climate change signals can be overwhelmed by other tree-mortality drivers

Determining the management and biophysical factors that mitigate tree mortality in urban forests is challenging. Nonetheless, tree mortality can be minimized by: (1) selecting suitable tree species for each site using information on species' climatic niche, tolerance and site requirements; (2) selecting high-quality planting stock that is free of defects and exhibits proper growth form; (3) using best practice planting techniques, which include assessing site conditions, applying rigorous planting protocols, monitoring plantings and adapting maintenance periods to specific site-conditions and species; and (4) providing long-term maintenance and monitoring to preserve existing urban trees. To assess mortality related to climate and extreme weather, we recommend experimental plantings or field trials where different factors can be controlled (McPherson et al., 2018). Also, developing long-term quantitative monitoring programs to conduct detailed assessments of species' growth and mortality rates, including plant health and performance after extreme weather events (e.g. heatwaves, storms). This dynamic monitoring can also be used to identify resilient and vulnerable species as well as susceptibility to pests and diseases in the context of climate change (**Table 1**).

Table 1. Key biophysical and management factors driving urban tree failure or mortality and recommendations for mitigation.

Tree failure/mortality driver	Description	Recommendation
Climate, average temperature and precipitation conditions over a period of 30 years.	Although human preferences influence the composition of urban forests (Sæbø et al., 2003), climate remains a key factor defining species' survival and performance in cities (Kendal et al., 2018).	Develop long-term monitoring plots stratified by different urban stressors to assess species' growth and performance. Identify the climate of origin or the climate niche of the species used for plantings to make informed decisions and decrease the probability of failure. For example, using species' climate niches, a global study found that more than half of species are potentially vulnerable to climate extremes in at least one city where they are currently planted (Esperon-Rodriguez et al., 2021a). Developing a species database with such species and their vulnerability at each location can be used to inform species selection (see **Box 1**).
Extreme weather events, which include severe or unseasonal precipitation events or drought; weather at (or beyond) the extremes of the historical climatology.	Extreme weather (e.g. heatwaves, flooding and storms) or drought can cause tree mortality and catalyse other factors that contribute to tree decline (Brando et al., 2014; Brandt et al., 2016; Jahani & Saffariha, 2021).	Conduct detailed assessments of species performance and condition after extreme weather events, with the aim of identifying resilient and vulnerable species. In China, over one thousand species were identified as being affected by extreme weather events (Yan & Yang, 2018). Including such risks in a species database can help inform species selection in different locations. In Iran, hazardous trees were identified as those affected by winds exceeding 100 km/hour (Jahani & Saffariha, 2021). Simulation models can identify the risk of tree failure in different habitats exposed to extreme storms caused by climate change.

Tree failure/mortality driver	Description	Recommendation
Improper species selection	Selecting unsuitable species can decrease the success of a planting and increase the associated cost of stewardship (McPherson et al., 2018).	Identify the climate origin or site requirements of the species used for plantings to make informed decisions and decrease the probability of failure. We recommend developing a database with species' climate of origin (e.g. country, climate zone, Köppen climate classification) and site requirements (e.g. soil volume, nutrients) to improve species selection across sites. Document successes and failures to identify resilient and vulnerable species. For this, we recommend long-term monitoring of tree performance and growth using standardized metrics (McPherson et al., 2016; van Doorn et al., 2020). These data should be linked to local climatic conditions by incorporating climate information (e.g. annual precipitation, mean annual temperature, maximum temperature) into the database.
Limited growth space for established trees	Inappropriate site conditions for current and future shoot and root growth increases the probability of tree failure (Jahani, 2017; Jahani, 2019; Hauer et al., 2020a; Hauer et al., 2020b; Hilbert et al., 2020).	Observe standard planting distances from urban structures and create proper soil rooting volume based on species' requirements before planting trees can help prevent tree failure. Develop and follow planting protocols considering species growth requirements. Assess tree growth through: (1) visual inspection to detect issues, symptoms and evaluate vitality; the investigation concludes if there are no issues observed; (2) when an issue is detected, further examination is required to confirm its nature; and (3) when the defect is confirmed and may represent a risk, it should be measured, recorded and recommendations made for corresponding actions, which may include tree removal.

Tree failure/mortality driver	Description	Recommendation
Pests and diseases	Pest and diseases may reduce tree growth and increase mortality. Climate change often increases their impact on trees (Tubby & Webber, 2010).	Periodic assessment of tree health and performance, particularly in the weeks following extreme weather events such as heatwaves and drought. We suggest incorporating a health or damage score into species' databases and monitoring changes through time. Short- and long-term monitoring is crucial for these assessments.
Poor quality of nursery material	High-quality stock is fundamental to promote tree growth and establishment, as poor material can harbour root and shoot issues and poor root to shoot balance that impair growth and survival, lead to structural failure and increase incidence of pathogens (Frampton et al., 2002).	Authorities and nurseries must collaborate in developing and applying rigorous standards for plant material. For example, the Australian national standard, AS2303 Tree Stock for Landscape Use, which specifies above- and below-ground criteria for assessing tree stock quality (AS 2303, 2018). Develop and implement standards for tree stock quality in collaboration with researchers, the nursery industry and other stakeholders.

Tree failure/mortality driver	**Description**	**Recommendation**
Inappropriate establishment techniques and insufficient maintenance	Disturbance from building/construction/service works that affect the root zone. Tree mortality can be associated with poor planting and maintenance techniques and practices, which exacerbate climate stresses (Roman et al., 2013; Breger et al., 2019).	Developing and applying rigorous and standardized planting protocols. These protocols can be adapted from existing urban forest data standards and inventory methods (McPherson et al., 1999; Keller & Konijnendijk, 2012). Protocols should be adaptable and flexible to meet different goals and needs, including those of practitioners, in the protocol development process as well as being simple for users (Roman et al., 2013). Monitoring plantings and adapting maintenance periods to specific site conditions and species' responses during the establishment phase. Growth data collected after planting and during the establishment and post-establishment phases (van Doorn & McPherson, 2018) can be used to examine relationships with factors such as site conditions and stewardship practices.
Poor site conditions	Poor site conditions, such as soil compaction, limited rooting volume and low nutrient availability can affect performance and reduce survival (Trowbridge & Bassuk, 2004; Hilbert et al., 2020).	Prior to planting, assess soil characteristics by determining pH, compaction, texture, water availability and nutrient status, among others, based on regional planting protocols. Sites with suboptimal conditions can be improved to meet standard planting conditions by identifying appropriate substrates, applying fertilisers and other amendments to enhance establishment and survival (Pauleit et al., 2002).

4. Conclusions

The ability to assess rates of climate change-driven mortality and decline can improve planting outcomes through the long-term survival and growth of urban forests with real environmental and socio-economic benefits. The threat of climate change, lack of inventory data, difficulties in discerning causes of tree dieback and mortality, and the need for monitoring have been established in the literature previously. Yet, we still do not currently have the necessary information on urban-tree resilience in the face of future climate change or the long-term monitoring data needed to detect and attribute climate change as a factor contributing to tree dieback and mortality in urban forests.

To maintain sustainable urban forests in a changing climate, it will be necessary to address economic considerations, to provide adequate time and effort for efficient and cost-effective establishment and maintenance of urban plantings, alongside consistent, detailed monitoring through time. We acknowledge, nevertheless, that the availability of the required information and tools will differ among locations and rely on access to financial resources. The use of big data methods based on remote sensing and integration with urban ecosystem accounting should be explored (e.g. Laumer et al., 2020; Hanssen et al., 2021).

More research is needed to identify future vulnerabilities of urban forests to a changing climate and emerging threats (e.g. invasive species, pollutants, wildfires). Urban tree inventories are necessary for successful urban-forest management, but they are insufficient to secure climate-resilient urban forests. Future research on the resilience of urban forests to climate change should incorporate multiple disciplines —including not only arborists, landscape architects and nursery owners, but other social science-based researchers and community practitioners– as central partners in the co-production of knowledge (Campbell et al., 2016). Therefore, future transdisciplinary vulnerability research and assessments on urban forest resilience to climate change will need to take into account more socio-ecological perspectives and approaches (Steenberg et al., 2017).

Determining the causes of tree mortality, or at least identifying and recording those cases in which climate might be a factor contributing to tree dieback and mortality, is fundamental for the maintenance and expansion of functional urban forests. Developing vulnerability metrics such as estimates of the thermal safety margins or vulnerability indices, as proposed here, represent some examples of new tools that can be implemented as a way forward. We call on governments, scientists and citizens to work together to develop detailed long-term monitoring plans for urban forests. Ultimately, the development of a knowledge base for understanding climate-driven failures requires dynamic assessments of urban forests on shorter timescales to enable policymakers and urban forest managers to better adapt and keep pace with rapid changes in climate. Given the longevity of trees in the landscape, future scenarios in which urban trees and forests are resilient or in decline will depend on the management and planning actions we make today.

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Author contribution

MER, PR, SP, MGT conceived the article. MER wrote the article. All authors contributed data and discussion of the content and reviewed or edited the manuscript before submission. Authors, excluding MER, PR, SP and MGT are listed alphabetically.

Competing Interests

The authors declare that they have no conflict of interest to disclose.

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Supporting Information

Materials and Methods

We conducted a systematic literature search on March 2020 to find studies reporting climate change as driver of urban tree mortality following the PRISMA approach (Liberati et al., 2009). We carried out a keyword and article title search using international (i.e. Google Scholar, JSTOR, ScienceDirect, Scopus, and the Web of Science) and domestic databases. The date range for searching was “all time” for keyword and title searches. The following topic search was used: (urban OR city) AND (tree OR “woody plant”) AND (species) AND (mortality) AND (symptom OR damage OR injury OR death) AND (climate change OR climate). Publications retrieved from these databases include journal articles, dissertations and conference proceedings. We performed a screening of the retrieved publications based on their titles and abstracts. We found no studies describing climate or climate change as cause of urban tree mortality and no long-term studies assessing the effect of climate change on urban tree dieback and mortality.

Results

Recommendations to identify climate change-driven failures and prevent urban tree mortality: Three approaches.

(1) Thermal Safety Margin. Using data on species’ climatic tolerance, the thermal safety margin (*S*) can be calculated. This metric indicates how much warmer (or drier), a city is or could become under climate change before the realised climate niche of its species will have been exceeded (Esperon-Rodriguez et al., 2019; Gallagher et al., 2019; Esperon-Rodriguez et al., 2021) and is calculated as follows:

$$S = Species_{\mathrm{Climate}} - City_{\mathrm{Climate}} \qquad (1)$$

where $Species_{Climate}$ is a measure of a species’ climatic limit for a given climatic variable, which can be estimated using the species’ climate niche based on occurrence records and current climatic conditions, and $City_{\mathrm{Climate}}$ is the current climate for a given variable. A positive safety margin ($S > 0$) indicates that the species has a thermal tolerance limit which exceeds current baseline temperature conditions in the focal city (e.g. cooler and thus safe); whereas a negative value ($S < 0$) indicates that the species is experiencing “unsafe” climatic conditions under the current climate (e.g. warmer than what the species can actually withstand according to its tolerance limit for temperature) (**Box 1**).

(2) Vulnerability Index. When data on species' tolerance are not available, a vulnerability index may be calculated using three components: (1) the number of individuals for a given species (V_N); (2) growth rate for a given period (V_{GR}); and (3) mortality rate for a given period (V_{MR}) (adapted from Esperón-Rodríguez & Barradas, 2015; Esperon-Rodriguez et al., 2019). A species is considered to be more vulnerable with a lower number of individuals, lower growth rates and high mortality rates than other species in a given urban forest inventory. This is a comparative vulnerability index (V_I) among species, where the highest vulnerability corresponds to 1 and the lowest to 0, and is estimated for the *i*th species planted in a city as:

$$V_I = \frac{V_N + V_{GR} + V_{MR}}{3} \qquad (2)$$

The first vulnerability component (i.e. V_N, number of individuals) is obtained by dividing the total number of individuals of *i*th species (N_i) by the greatest number of individuals among all species (N_{MAX}):

$$V_N = 1 - \frac{N_i}{N_{MAX}} \qquad (3)$$

The vulnerability component for growth rate (V_{GR}) is obtained by dividing the growth rate of the *i*th species during a given time period (GR_i) by the highest growth rate among all species (GR_{MAX}):

$$V_{GR} = 1 - \frac{GR_i}{GR_{MAX}} \qquad (4)$$

Similarly, the vulnerability component for mortality rate (V_{MR}) is obtained by dividing the mortality rate of the *i*th species during a given time period (MR_i) by the highest mortality rate among all species (MR_{MAX}):

$$V_{MR} = \frac{MR_i}{MR_{MAX}} \qquad (5)$$

Species then can be ranked from high ($V_I = 1$) to low ($V_I = 0$) overall vulnerability. An example for this estimation is given in **Table S1** where we compare the number of individuals, growth (cm/year) and mortality (number of dead individuals/year) rates of five species in a given city during the given time period.

We acknowledge some final considerations to our approaches. First, the thermal safety margin can be implemented for other climatic variables, such as annual precipitation, the precipitation of the driest quarter, and even potential evapotranspiration (Esperon-Rodriguez et al., 2019; Esperon-Rodriguez et al., 2021). Second, in regards to the vulnerability index, species have different relative growth rates, therefore the growth rate component might become skewed. The growth rate of a slow, but stress-tolerant species, will be lower than that of a fast-growing competitor species (i.e. fast-slow spectrum perspective). Therefore, fast-growing and rather not so stress-tolerant species might be ranked with lower risk compared to more slow-growing but stress-tolerant species (e.g. species better adapted to drought) as such adaptions generally are costlier (slow) for plants. In those cases, an alternative is to use a species relative measure, such as the maximum growth for the species observed during a given time period. Finally, regarding the mortality component, caution is warned when comparing mortality rates during establishment versus other time periods. For this assessment, we also suggest developing an uncertainty analysis, so that rare species that will inevitably have wider confidence or credibility intervals, will not be overrepresented.

Table S1. Comparison of growth rate (GR; cm/year), mortality rate (MR; number of dead individuals/year) of five species in a city, and their values for their vulnerability index (V_I), vulnerability of number of individuals (V_N), vulnerability for growth rate (V_{GR}) and vulnerability for mortality rate (V_{MR}). The vulnerability index (V_I) allows the ranking of species, where species A and C are ranked as the least and most vulnerable, respectively.

Species	No. trees	GR	MR	V_N	V_{GR}	V_{MR}	VI	Rank
Species A	984	1.2	2	0	0	0.50	0.17	5
Species B	234	0.9	4	0.76	0.25	1	0.67	2
Species C	45	0.5	3	0.95	0.58	0.75	0.76	1
Species D	225	1.1	1	0.77	0.08	0.25	0.37	4
Species E	679	0.7	2	0.31	0.42	0.50	0.41	3

(3) Integration of Thermal Safety Margin and Vulnerability. When available, integration of species' tolerance into the vulnerability index by adding the species' thermal safety margin for climate. The vulnerability component for species' safety margin (V_{SSM}) is obtained by dividing the species' safety margin of the *i*th species for a given climate variable (e.g. MAT, AP) ($S_{Climate}$) by the highest species' safety margin among all species ($S_{ClimateMAX}$):

$$V_{SSM} = \frac{S_{Climate}}{S_{ClimateMAX}} \qquad (6)$$

The vulnerability index (V_I) among species is estimated for the *i*th species planted in a city as:

$$V_I = \frac{V_N + V_{GR} + V_{MR} + V_{SSM}}{4} \quad (7)$$

An integrated example for this estimation is given in **Table S2** where we compare the number of individuals, growth (cm/year) and mortality (number of dead individuals/year) rates, and species' safety margin (MAT) of five species in a given city during the given time period.

Table S2. Comparison of growth rate (GR; cm/year), mortality rate (MR; number of dead individuals/year) species' thermal safety margin (for mean annual temperature, S_{MAT}) of five species in a city, and their values for their vulnerability index (V_I), vulnerability of number of individuals (V_N), vulnerability for growth rate (V_{GR}), vulnerability for mortality rate (V_{MR}) and vulnerability for species' safety margin (V_{SSM}). The vulnerability index (V_I) allows the ranking of species, where species A and C are ranked as the least and most vulnerable, respectively.

Species	**No. trees**	**GR**	**MR**	S_{MAT}	V_N	V_{GR}	V_{MR}	V_{SSM}	V^I	**Rank**
Species A	984	1.2	2	5	0	0	0.50	0	0.17	5
Species B	234	0.9	4	-3	0.76	0.25	1	0.6	0.67	4
Species C	45	0.5	3	-2.5	0.95	0.58	0.75	-0.5	0.76	1
Species D	225	1.1	1	3	0.77	0.08	0.25	-0.6	0.37	2
Species E	679	0.7	2	2.1	0.31	0.42	0.50	0.42	0.41	3

In the following example, we used data from an urban tree inventory, which includes changes in diameter at breast height (DBH) for the period 2013 -2020 for 66 species. Growth rate (GR) was averaged for each species and was estimated as:

$$GR = \frac{DBH_{2020} - DBH_{2013}}{DBH_{2013}} \qquad (8)$$

Based on previous research (Esperon-Rodriguez et al., 2019), we estimated the species' safety margin (Eq 1) for mean annual temperature (S_{MAT}). We found that 14 species are already exceeding their safety margin, experiencing unsafe conditions in this example city (**Box 1**). Data on tree mortality were not available, thus the vulnerability index was estimated using the number of trees, growth rate (i.e. DBH) and safety margin (**Table S3**).

We identified *Brachychiton populneus* and *Casuarina cunninghamiana* as the most vulnerable species in this city, whereas *Corymbia maculata* and *Pistacia chinensis* were the least vulnerable. We found negative, significant correlations between the vulnerability index (V_I) with growth rate (GR) and the species' that presently are exceeding their safety margin for mean annual temperature ($S_{MAT} < 0$), where species with slow GR were more vulnerable. Similarly, high vulnerability was associated with increased species' thermal safety margin (**Figure S1**).

Table S3. Number of trees (trees), growth rate (GR; DBH, cm/year), species' thermal safety margin (for mean annual temperature, S_{MAT}, °C), current risk based on S_{MAT} of 66 species in a city, and their values for their vulnerability index (V_I), vulnerability of number of individuals (V_N), vulnerability for growth rate (V_{GR}), and vulnerability for species' safety margin (V_{SSM}). The vulnerability index (V_I) allowed the ranking of species.

Species	Trees	GR_{DBH}	S_{MAT}	V_N	V_{GR}	V_{SSM}	V^I	Rank
Brachychiton populneus	500	0.09	5.16	0.99	0.95	0.88	0.94	1
Casuarina cunninghamiana	5832	0.16	5.16	0.93	0.91	0.88	0.91	2
Sapium sebiferum	9488	0.23	5.56	0.89	0.88	0.95	0.90	3
Araucaria cunninghamii	1661	0.05	4.36	0.98	0.97	0.74	0.90	4
Liquidambar styraciflua	7123	0.09	4.76	0.91	0.95	0.81	0.89	5
Washingtonia robusta	6756	0.06	4.56	0.92	0.97	0.78	0.89	6
Lagerstroemia indica	15725	0.31	5.86	0.81	0.84	1.00	0.88	7
Cupaniopsis anacardioides	17980	0.19	5.56	0.78	0.90	0.95	0.88	8
Ficus macrophylla	1385	0.31	4.76	0.98	0.83	0.81	0.88	9
Eucalyptus nicholii	94	0.05	-3.84	1.00	0.97	0.65	0.88	10
Ulmus glabra	302	0.08	-3.84	1.00	0.96	0.65	0.87	11
Brachychiton rupestris	346	0.23	4.26	1.00	0.88	0.73	0.87	12
Callistemon salignus	1870	0.30	4.46	0.98	0.84	0.76	0.86	13
Eucalyptus saligna	3504	0.08	3.86	0.96	0.96	0.66	0.86	14
Schinus molle	1508	0.17	3.96	0.98	0.91	0.68	0.86	15
Callistemon citrinus	734	0.32	4.36	0.99	0.83	0.74	0.86	16
Corymbia citriodora	9510	0.17	4.46	0.89	0.91	0.76	0.85	17
Banksia integrifolia	5550	0.13	3.96	0.93	0.93	0.68	0.85	18
Ulmus parvifolia	10602	0.16	4.36	0.87	0.92	0.74	0.84	19
Stenocarpus sinuatus	4543	0.23	4.16	0.95	0.88	0.71	0.84	20
Ficus rubiginosa	11418	0.24	4.66	0.86	0.87	0.80	0.84	21
Eucalyptus robusta	2842	0.32	4.26	0.97	0.83	0.73	0.84	22
Populus alba	485	0.14	-3.54	0.99	0.93	0.60	0.84	23
Agathis robusta	1999	0.24	3.86	0.98	0.87	0.66	0.84	24
Brachychiton acerifolius	4212	0.08	3.36	0.95	0.96	0.57	0.83	25
Jacaranda mimosifolia	31218	0.15	5.46	0.62	0.92	0.93	0.82	26
Brachychiton discolor	1204	0.26	3.56	0.99	0.86	0.61	0.82	27
Corymbia eximia	1758	0.39	-3.94	0.98	0.79	0.67	0.81	28
Buckinghamia celsissima	648	0.70	4.76	0.99	0.63	0.81	0.81	29
Platanus orientalis	2110	0.07	2.56	0.97	0.96	0.44	0.79	30
Robinia pseudoacacia	568	0.39	3.36	0.99	0.80	0.57	0.79	31
Fraxinus excelsior	350	0.17	2.56	1.00	0.91	0.44	0.78	32
Pittosporum undulatum	326	0.32	2.96	1.00	0.83	0.51	0.78	33
Callistemon viminalis	12770	0.73	4.96	0.85	0.61	0.85	0.77	34
Melaleuca quinquenervia	30609	0.36	4.86	0.63	0.81	0.83	0.76	35
Quercus palustris	2023	0.14	-2.04	0.98	0.92	0.35	0.75	36

Species	**Trees**	**GR_{DBH}**	**S_{MAT}**	**V_N**	**V_{GR}**	**V_{SSM}**	**V^I**	**Rank**
Corymbia ficifolia	715	0.09	-1.74	0.99	0.95	0.30	0.75	37
Melaleuca linariifolia	2170	0.07	1.76	0.97	0.96	0.30	0.75	38
Phoenix canariensis	1710	0.03	1.56	0.98	0.99	0.27	0.74	39
Celtis occidentalis	2050	0.21	-2.14	0.98	0.89	0.36	0.74	40
Eucalyptus grandis	543	0.17	1.56	0.99	0.91	0.27	0.72	41
Harpephyllum caffrum	205	0.25	-1.64	1.00	0.87	0.28	0.71	42
Syzygium paniculatum	3097	0.17	1.46	0.96	0.91	0.25	0.71	43
Eucalyptus leucoxylon	136	0.23	-1.44	1.00	0.88	0.25	0.71	44
Eucalyptus scoparia	2646	0.36	1.96	0.97	0.81	0.33	0.70	45
Eucalyptus botryoides	2612	0.18	1.26	0.97	0.91	0.22	0.70	46
Casuarina glauca	4283	0.18	1.16	0.95	0.90	0.20	0.68	47
Populus simonii	16959	0.12	-1.64	0.80	0.94	0.28	0.67	48
Magnolia grandiflora	14274	0.25	1.76	0.83	0.87	0.30	0.67	49
Pyrus calleryana	3021	0.15	0.36	0.96	0.92	0.06	0.65	50
Ginkgo biloba	1427	0.15	0.26	0.98	0.92	0.04	0.65	51
Archontophoenix cunninghamiana	4984	0.52	1.56	0.94	0.72	0.27	0.64	52
Eucalyptus sideroxylon	3598	0.47	1.26	0.96	0.75	0.22	0.64	53
Flindersia australis	11453	0.45	1.56	0.86	0.76	0.27	0.63	54
Koelreuteria paniculata	9013	0.18	0.46	0.89	0.90	0.08	0.62	55
Eucalyptus punctata	1026	0.42	-0.64	0.99	0.78	0.11	0.62	56
Celtis australis	14767	0.07	0.46	0.82	0.96	0.08	0.62	57
Liriodendron tulipifera	3177	0.30	-0.24	0.96	0.84	0.04	0.61	58
Fraxinus pennsylvanica	11762	0.17	-0.34	0.86	0.91	0.06	0.61	59
Angophora costata	17529	0.18	0.46	0.79	0.90	0.08	0.59	60
Lophostemon confertus	82979	0.15	4.96	0.00	0.92	0.85	0.59	61
Backhousia citriodora	3122	0.73	1.06	0.96	0.61	0.18	0.59	62
Tristaniopsis laurina	54600	0.23	2.56	0.34	0.88	0.44	0.55	63
Elaeocarpus reticulatus	29003	0.23	-0.24	0.65	0.88	0.04	0.52	64
Corymbia maculata	39159	0.31	0.96	0.53	0.84	0.16	0.51	65
Pistacia chinensis	13263	1.89	2.46	0.84	0.00	0.42	0.42	66

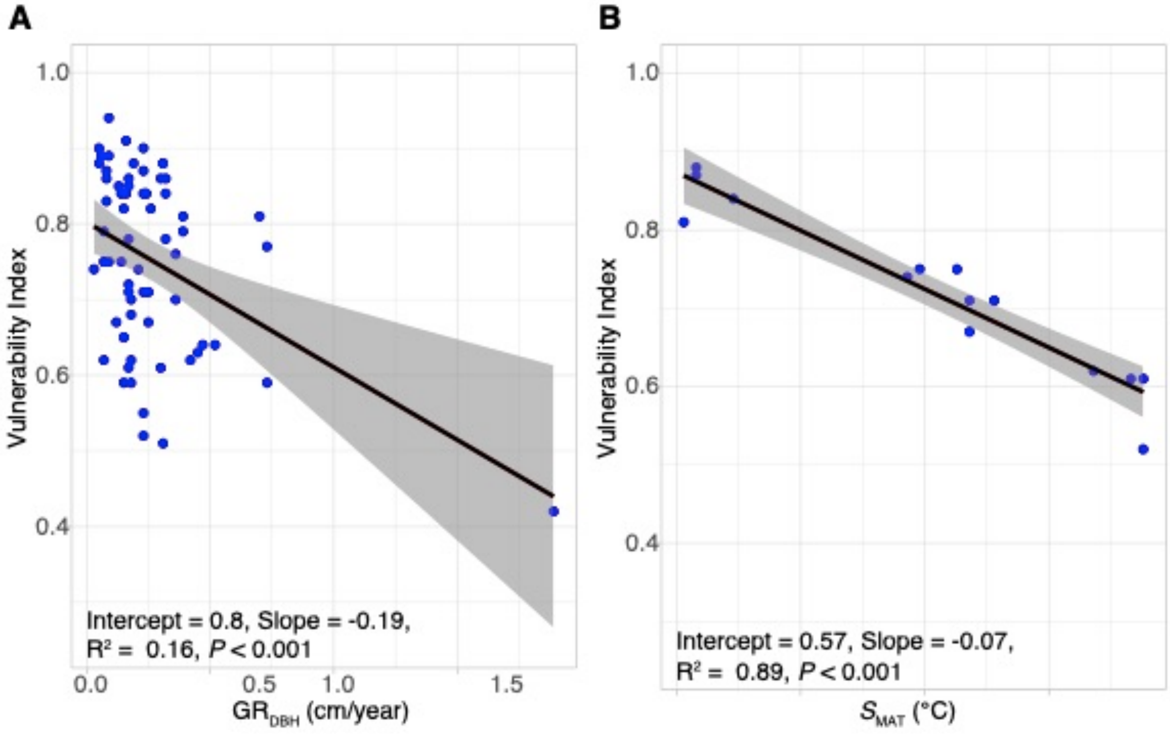

Figure S1. Relationship between the vulnerability index and (**A**) growth rate of diameter at breast height (GR_{DBH}; *N* = 66 species) and (**B**) species' their safety margin for mean annual temperature (S_{MAT}; N = 14 species presently are exceeding their safety margin for mean annual temperature, $S_{MAT} < 0$). Ribbons indicate the 95% confidence interval for predictions from a linear model ["lm"].

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