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Limiting the impact of insect pests on urban trees under climate change

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ABSTRACT

Insect herbivore pests have been identified as a significant threat to the health and survival of urban trees. In the future, these pest-tree interactions in urban areas may be altered by the increased variability in environmental conditions projected under climate change. However, our understanding of how this may occur is limited. In this short communication, we discuss the factors that increase urban forest vulnerability to insect pests and how climate change will alter these factors. We then discuss how we can help to reduce the negative effects of these factors through actions such as diversifying our urban forests, reducing plant stress and increasing our capacity for early detection of insect pests using emerging biosurveillance technologies. In a time with increasing globalisation aiding in the transport of pests between urban areas, it is important that we remain vigilant to the ever-increasing threats that can compromise our urban green assets and the benefits they provide.

1. Introduction

Urban forests provide a range of social, health, economic and environmental benefits that can substantially improve the liveability of urban areas and human well-being (Salmond et al. 2016). As a result, there has been an increasing investment in urban green infrastructure globally (e.g. European Union's 3 billion trees by 2030, Australia's 202020 Vision, The United States' Urban and Community Forestry Program). In order to continue to reap the benefits urban forests provide, we must maintain the health and survival of the trees that comprise them.

A prominent emerging threat to the health and survival of urban trees is insect herbivore pests (Raum et al. 2023). For example, it is projected that insect pests will kill 1.4 million trees in the United States between 2020 and 2050 and cost on average $USD 30 million to manage annually (Hudgins et al. 2022). The impacts of insect pests on urban trees include defoliation, branch loss, and in extreme cases, tree mortality. This may reduce the ecosystem services that urban trees provide as well as cause safety risks (e.g., falling limbs) and diminish the aesthetic appeal of urban areas (Boyd et al. 2013).

Climate change is projected to increase variability in environmental conditions (e.g. temperature, rainfall patterns) globally. For example, extreme climatic events are projected to increase in intensity and frequency under climate change (Fineschi and Loreto, 2020). It is well-documented that these climate change-associated shifts in environmental conditions have a significant effect on plant-insect interactions in natural forests (Klapwijk et al. 2013; Hamann et al. 2020). In contrast, empirical studies on the effect of climate change on insect pests in urban forests are lacking, although the potential risk it poses has been recognised (Tubby and Webber, 2010; Frank and Just, 2020). This short communication explores the mechanisms by which climate change may exacerbate the damage caused by insect pests on urban trees as well as management suggestions to reduce these negative impacts.

2. What factors increase urban forest vulnerability to insect pests? How will these factors be altered under climate change?

2.1. Low vegetation diversity and complexity in urban areas

Many urban forests are characterised by low plant diversity and complexity (Hou et al. 2023). As a result, urban forests are more vulnerable to the impacts of insect pests than surrounding natural forests (Hanks and Denno, 1993; Raupp et al. 2010). For example, based on urban tree inventories of ten major Nordic cities, Sjöman and Östberg (2019) found that an outbreak of Asian longhorned beetle (Fig. 1) and citrus long-horned beetle would cause 98% loss of trees in the worst-case scenario. The success of insect pests in urban areas with low plant diversity and complexity can be explained by two hypotheses: the biotic resistance hypothesis and the enemies hypothesis. The biotic resistance hypothesis states that more complex habitats limit the niche space available to other species, which in turn prevents the invasion of insect

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pests (Levine and D'Antonio, 1999). The natural enemies hypothesis, on the other hand, states that more complex habitats support a greater abundance of predatory insects, which in turn greatly regulates insect pests (Root, 1973). It has been shown that natural enemies are often less abundant and diverse in urban areas, which may reduce the top-down regulation of insect pests in these areas (Hanks and Denno, 1993; Parsons et al. 2020, Shrewsbury and Raupp, 2006, but see Dale and Frank 2014b).

In many urban areas, climate change is predicted to cause a reduction in suitable habitat for several tree species (Esperon-Rodriguez et al., 2021), which may reduce urban forest diversity even further, unless there is proactive planting. Although many urban forestry practitioners believe climate change is a serious threat to the survival of urban forests, there is much uncertainty as to which species will thrive under future climates (Khan and Conway, 2020). Even with certainty, there is often a lag time between what practitioners would like to plant and what is available commercially, therefore species that are already available and widely planted are often favoured. To increase the resilience of urban forests to the threat of insect pests in general and under climate change, it is imperative that diversity, at the species, genetic and structural levels, is increased (Tabassum et al. 2023).

2.2. *Stressful environmental conditions for tree growth in urban areas*

The environmental conditions (e.g. pollution, soil compaction, low soil moisture) that characterise urban areas can make it difficult for poorly adapted trees to thrive (Locosselli et al. 2019; Gao et al. 2023). For example, urban areas can be up to 10°C warmer than surrounding rural areas due to their impervious surfaces absorbing heat, the presence of anthropogenic heat sources and low vegetation cover. This phenomenon, known as the urban heat island effect (Kim, 1992), can reduce soil moisture and increase vapour pressure deficit, causing drought-like conditions (Cregg and Dix, 2001). In urban areas that become hotter and receive less rainfall under climate change, these drought-like conditions may be exacerbated, which will place further stress on urban trees that are not drought-tolerant.

When trees experience stress, their ability to produce secondary metabolites is often compromised. This is important in tree-pest interactions because secondary metabolites often act as deterrents to pests. There are a range of conflicting hypotheses (e.g., carbon nutrient balance, growth-differentiation balance, plant stress) that attempt to predict how stressful environmental conditions alter secondary metabolite production in plants. Unfortunately, these hypotheses are too simplistic to be universally applicable (Hamilton et al., 2001) or are difficult to test rigorously (Stamp, 2004) due to the multifunctional nature of plant secondary metabolites (Erb and Kliebenstien, 2020). Further, another layer of complexity is added when the "disease triangle" concept is considered (Stevens, 1960), as it incorporates the interaction of pests with the environment into the equation. This means that although plants may have a reduced capacity to defend themselves under stressful environmental conditions, it does not necessarily make them more vulnerable to insect attack because the pests may also experience stress. This may explain the contradictory findings reported by studies examining tree-pest interactions in urban areas, with some studies finding positive effects of plant stress on insect pest performance (Cregg and Dix, 2001; Dale and Frank, 2017) and others finding the opposite (Hanks and

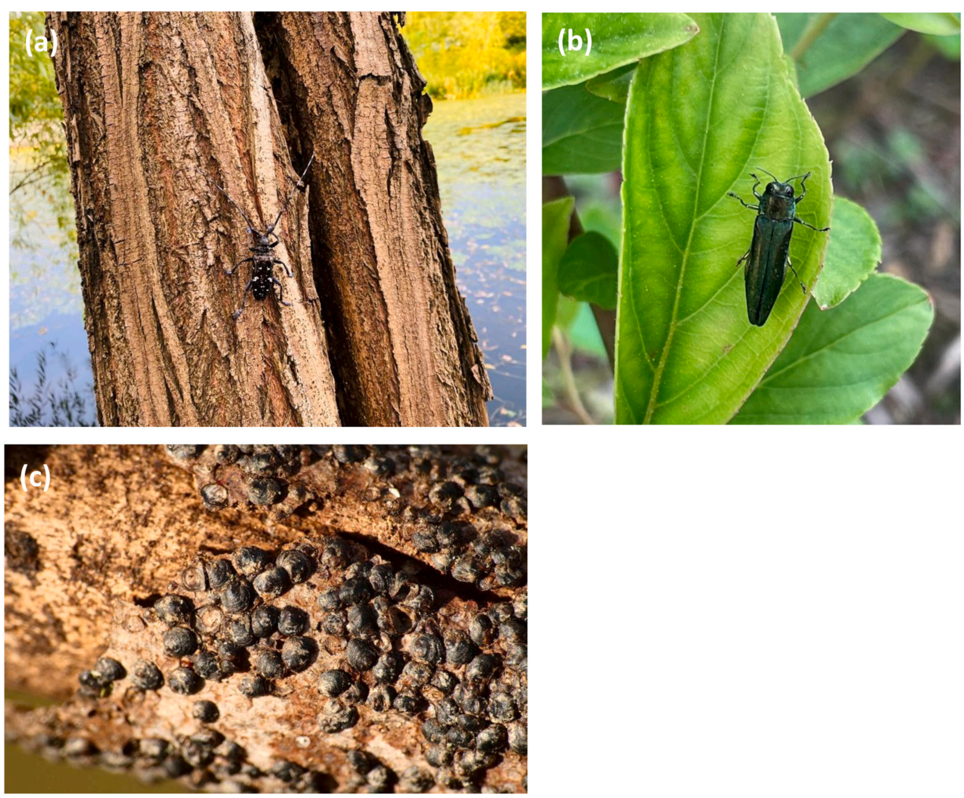

Fig. 1. Examples of insect pests found on urban trees. (a) Asian longhorned beetle (*Anoplophora glabripennis*) is a wood-boring species originating from Asia. It has been found to infest a plethora of popular tree genera found in urban landscapes including *Acer*, *Ulmus*, *Betula* and *Platanus*. Luckily, eradication programs have proven successful but reintroductions continue to occur (Haack et al. 2010) (image credit: timashtree, GBIF). (b) Emerald ash borer (*Agrillus planipennis*) is another wood-boring species originating from Asia. It exclusively feeds on trees from the genus *Fraxinus*, a popular urban tree genus. It is projected that the emerald ash borer will be responsible for 90% of the 1.4 million urban tree mortalities in the United States between 2020 and 2050 (Hudgins et al. 2022) (image credit: modlazak, GBIF). (c) Gloomy scale (*Melanaspis tenebricosa*) is a sap-sucking insect native to southeastern United States but has been found to thrive in urban areas where they prey on red maples. They have been observed to be expanding in their urban range, possibly due to climate change (Yang and Bou-Zeid, 2018; Frank and Just, 2020). Heavy infestations can cause branch dieback and ultimately endanger the life of the tree (Frank and Just, 2020) (image credit: David, GBIF).

Denno, 1993; Meineke and Frank, 2018). Given the myriad of contributing factors that influence plant-pest interactions, predicting their outcomes in response to climate change is difficult and not well understood. This highlights the need for a multi-pronged approach that incorporates species diversification, abiotic stress reduction (e.g. soil additives, irrigation) and improved pest detection to keep urban forests safe from the threat of pest outbreaks as the climate changes.

2.3. Altered environmental conditions facilitating insect pest outbreaks in urban areas

Insect development and survival are highly dependent on abiotic environmental conditions such as temperature (Tubby and Webber, 2010). For example, the higher temperatures in urban areas hasten insect metabolic rates, which increases the survival and fecundity of and decreases the development time of insect pests, making urban trees more vulnerable to attack (Raupp et al. 2010; Tubby and Webber, 2010). Evidence of such changes has been documented, with studies finding increases in density and fecundity of urban tree insect pests (e.g., Meineke et al. 2013; Dale and Frank 2014a,b; Youngsteadt et al., 2014; Dale et al. 2016, but see Parsons et al. 2020). Further, these changes may be exacerbated under water-limiting conditions typical of urban areas. For example, Dale and Frank (2017) found that female embryo production and body size of the gloomy scale (*Melanaspis tenebricosa*, Fig. 1) not only increased with temperature but was also greater on water-stressed than well-watered urban trees. Concerningly, these environmental conditions that enhance insect pest success are likely amplified in urban areas that become hotter and receive less rainfall under climate change. As a result, insect pests may be able to adapt to climate change faster than their host plants (Tubby and Webber, 2010), which could have dire consequences for the health and survival of urban forests.

The shift in environmental conditions under climate change may allow insect pests to increase their climatically suitable geographic ranges (Tubby and Webber, 2010; Frank and Just, 2020). For example, *M. tenebricosa* has been found to occur further north and at higher altitudes than previously described, possibly as a result of climate change and the urban heat island effect raising winter temperatures in urban areas (Yang and Bou-Zeid, 2018; Frank and Just, 2020). In extreme cases, these range expansions could lead to outbreaks of insect pests in urban areas where they currently do not pose a significant threat (Tubby and Webber, 2010). However, climate change may also have the opposite effect, with some insect pests experiencing a halt or contraction in their range due to them reaching their thermal maxima (Tobin et al. 2014; Mech et al. 2018).

In addition to the direct effects climate change may have on insect pests in urban areas, it may have an indirect effect on insect pests by causing a mismatch between their lifecycles and those of their enemies. For example, Meinenke et al. (2014) found that the oak lecanium scale (*Parthenolecanium quercifex*) oviposited earlier in the season on warmer urban trees, however, the phenology of its parasitoid enemy did not similarly advance. This breakdown in synchronicity could lead to reduced top-down regulation of insect pests by their enemies, enabling pest numbers to proliferate.

3. How can we reduce the threats of insect pests in urban areas under future climate change?

Climate change is predicted to influence plant-insect interactions in urban areas (Tubby and Webber, 2010). Some pest insect species are expected to increase in abundance and geographic range while for many others, the impact of climate change is unknown due to lack of research and/or the complicated nature of ecological interactions. Therefore, we must take precautionary action and increase the resilience of our urban forests to insect pests to ensure that they continue to provide their valuable ecosystem services. Below we provide a range of suggestions to help achieve this goal.

3.1. Diversification of urban forests

The nursery industry is required to produce large quantities of tree stock rapidly, which often means only a handful of species are propagated. Reduced tree species diversity in urban areas, to the point where there are only a handful of preferred species, has been shown to predispose urban forests to insect pest outbreaks (Paap et al. 2017; Raum et al. 2023). Climate change is expected to further decrease tree diversity, without the planting of new tree species, as species lose suitable habitat in urban areas (Esperon-Rodriguez et al., 2021). In order to increase diversity, species that will thrive in future climates need to be identified (Tabassum et al. 2023). Species should be identified based on the growth strategies and traits that are required to thrive in the urban area of interest rather than the climate envelope in which species exist in nature (Hanley et al. 2021). It is also important to identify species that will add structural diversity (i.e. complexity) to urban areas. In many cases, exotic species will be identified given that native species are adapted to the current climate conditions of the area they originate from. However, using these species comes with the trade-off that they may introduce novel insect pests into an area (Turbelin et al. 2022). To facilitate the diversification of urban forests, it is critical strategies are developed to educate urban forest practitioners and the general public about the importance of increasing diversity in urban forests (Tabassum et al. 2023).

It should be noted that increasing the diversity of urban forests will likely take decades, as existing tree species will need to be removed and replaced with new species that will need to establish before providing ecosystem services. This transition may be further complicated by the dynamic nature of climate change through time. Therefore, the conservation of diverse natural forest remnants within urban areas should also be made a priority to act as diversity buffers.

3.2. Reduce urban tree stress

The environmental conditions that characterise urban areas may cause tree stress, making them more susceptible to insect pest attacks. Therefore, reducing tree stress in urban areas by improving growing conditions should be a priority. Several management strategies can be utilised by urban forest practitioners to improve the growing conditions for urban trees, including the use of mulch, supplemental irrigation and soil additives. It is suggested that these management actions remain consistent throughout the lifespan of urban trees, as a reactive response to abiotic stress could cause more harm. For example, the pulsed stress hypothesis proposes that periods of drought stress followed by watering, increase the nitrogen content of phloem sap, making trees more appealing to insect pests (Raupp et al. 2010). Prioritising the provisioning of a stable budget to implement these management strategies should be the priority for municipalities (Raum et al. 2023). Unfortunately, municipalities have a finite budget when it comes to tree asset maintenance and pest management, which may make a proactive approach difficult to sustain.

3.3. Improve insect pest detection

The global trade in live plants through the nursery industry is amongst the most prevalent source of introduced plant insect pests around the world (Brasier, 2008; Turbelin et al. 2022). Urban areas are often the first point of contact for introduced pests as human movement, international trade and imported nursery stock are often concentrated in these areas (Colunga-Garcia et al. 2010). Most introduced insects remain benign, however, the impact of climate change on environmental conditions in cities could result in some introduced insects becoming serious problems (Tubby and Webber, 2010). Once established in urban forests, pests may migrate to natural forests, at which point, management and eradication efforts become extremely challenging (Dodds and Orwig, 2011). Therefore, the ability to detect and eradicate exotic insects before they are established in urban areas will be the best line of defence.

Inspections of imported plant stock are generally based on visual inspections of symptoms of known quarantine risks (Paap et al. 2017). However, this system is inherently flawed for several reasons. Firstly, for an organism to be regulated against, it must already be known to be harmful. Hence, it does not take into account organisms that may be benign in their native ranges but become problematic pests when introduced into new environments, nor the effect of climate change on pest emergence (Brasier, 2008; Paap et al. 2017). Secondly, the proportion of plants in a shipment that is required to be visually inspected also differs depending on the country, with some countries such as Australia and New Zealand having stricter requirements than others such as the United States (Eschen et al. 2015). Further, even with strict requirements, there is a limit to the amount of plant material that can be inspected before entry. Finally, visual inspections of plant matter are not always guaranteed to identify threats such as pests with inconspicuous life stages (Eschen et al. 2015). Moreover, many exporting nurseries use pesticides that suppress but do not kill pests, with the aim of presenting symptom-free, healthy-looking plants (Brasier, 2008).

Despite the flaws associated with the current detection methods, the early detection of pests is improving as emerging biosurveillance techniques are being adopted. Mobile surveillance units, also known as sentinels, are being used to sample airborne insects and reference them against current environmental conditions to provide real-time data on insect pests in a particular area (e.g. iMapPESTS Sentinel in Australia). Remote sensing using satellites (e.g. Sentinel-2) and drones is also proving to be a useful technique in detecting and monitoring insect pests (Zhang et al. 2019). Finally, the use of environmental DNA metabarcoding has already proven to be useful in the early detection of insect pest species (Young et al. 2021). All of these techniques also provide critical information about the patterns of entry and spread of pests, which helps optimise risk-based inspections (Mastin et al. 2020). Further optimization may be possible by increasing the transparency in the reporting of inspection and detection rates across countries.

A proactive approach is to identify problematic pests before they even enter a country. This can be achieved with the use of horizon scanning, which is a systematic search for potential threats that are currently not well known (Sutherland and Woodroof, 2009). Horizon scanning for urban pests that are problematic in other countries and how they will interact with climate change in novel environments presents a potential avenue for flagging dangerous imports. In cases where a significant pest threat is identified, biosurveillance on the potential introduction pathways of the pest can be ramped up. The effectiveness of this strategy could be enhanced by using the knowledge we have on the pest's previous invasions (e.g. introduction pathway) to inform where the biosurveillance should be focused. Understanding imminent threats will allow the prioritisation of limited resources that many agencies have in terms of early detection but will require scientists, government officials and policy-makers to work in tandem to achieve such goals.

4. Concluding remarks

Pests constitute a significant threat to tree health, growth and survival in urban areas and may impact the ecosystem services they can deliver. Climate change adds an additional layer of complexity as it may interrupt trophic interactions, impact host plant condition and alter abiotic environmental conditions, potentially providing circumstances for insect pests to proliferate. It is important that we effectively control insect pests in urban areas to not only allow trees to thrive and continue providing their beneficial services but also to ensure pests do not migrate to natural forests. Understanding how climate change will affect insect pest-host interactions in urban areas is paramount to increasing our ability to safeguard our urban tree assets.

CRediT authorship contribution statement

Leishman Michelle: Conceptualization, Supervision, Writing – review & editing. **Manea Anthony:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Tabassum Samiya:** Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

We declare that none of the authors have competing financial or non-financial interests.

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References

Boyd, I.L., Freer-Smith, P.H., Gilligan, C.A., Godfray, H.C.J., 2013. The consequences of tree pests and diseases for ecosystem services. Science 342, 1235773. https://doi.org/10.1126/science.1235773.

Brasier, C.M., 2008. The biosecurity threat to the UK and global environment from international trade in plants. Plant Pathol. 57, 792–808. https://doi.org/10.1111/j.1365-3059.2008.01886.x.

Colunga-Garcia, M., Magarey, R.A., Haack, R.A., Gage, S.H., Qi, J., 2010. Enhancing early detection of exotic pests in agricultural and forest ecosystems using an urban-gradient framework. Ecol. Appl. 20, 303–310. https://doi.org/10.1890/09-0193.1.

Cregg, B.M., Dix, M.E., 2001. Tree moisture stress and insect damage in urban areas in relation to heat island effects. J. Arboric. 27, 8–17.

Dale, A.G., Frank, S.D., 2014b. Urban warming trumps natural enemy regulation of herbivorous pests. Ecol. Appl. 24, 1596–1607. https://doi.org/10.2890/13-1961.1.

Dale, A.G., Frank, S.D., 2014a. The effects of urban warming on herbivore abundance and street tree condition. PLoS ONE 9, e102996. https://doi.org/10.1371/journal.phone.0102996.

Dale, A.G., Frank, S.D., 2017. Warming and drought combine to increase pest insect fitness on urban trees. PLoS ONE 12, e0173844. https://doi.org/10.1371/journal.pone.0173844.

Dale, A.G., Youngsteadt, E., Frank, S.D., 2016. Forecasting the effects of heat and pests on urban trees: impervious surface thresholds and the 'pace-to-plant' technique. Arboric. Urban For. 42, 181–191 doi:10.

Dodds, K.J., Orwig, D.A., 2011. An invasive urban forest pest invades natural environments-Asian longhorned beetle in northeastern US hardwood forests. Can. J. For. Res. 41, 1729–1742. https://doi.org/10.1139/x11-097.

Erb, M., Kliebenstien, D.J., 2020. Plant secondary metabolites as defenses, regulators and primary metabolites: the blurred functional trichotomy. Plant Physiol. 184, 39–52. https://doi.org/10.11104/pp.20.00433.

Eschen, R., Britton, K., Brockerhoff, E., Burgess, T., Dalley, V., et al., 2015. International variation in phytosanitary legislation and regulations governing importation of plants for planting. Environ. Sci. Policy 51, 228–237. https://doi.org/10.1016/j.envsci.2015.04.021.

Esperon-Rodriquez, M., Baumgartner, J.B., Beaumont, L., Lenoir, J., Nipperess, D., et al., 2021. Climate-change risk analysis for global urban forests. Nat. Clim. Change 12, 950–955. https://doi.org/10.1038/s41558-022-01465-8.

Fineschi, S., Loreto, F., 2020. A survey of multiple interactions between plants and the urban environment. Front. For. Glob. Change 3, 30. https://doi.org/10.3389/ffgc.2020.00030.

Frank, S.D., Just, M.G., 2020. Can cities activate sleeper species and predict future forest pests? A case study of scale insects. Insects 11, 142. https://doi.org/10.3390/insects11030142.

Gao, X., Zhao, B., Chen, Z., Song, W., Li, Z., et al., 2023. The impact of urbanization on tree growth and xylem anatomical characteristics. Biol. (Basel) 12, 1373. https://doi.org/10.3390/biology12111373.

Haack, R.A., Hérard, F., Sun, J., Turgeon, J.J., 2010. Managing invasive populations of Asian Longhorned Beetle and Citrus Longhorned Beetle: A worldwide perspective. Annu. Rev. Entomol. 55, 521–546. https://doi.org/10.1146/annurev-ento-112408-085427.

Hamann, E., Blevins, C., Franks, S.J., Jameel, M.I., Anderson, J.T., 2020. Climate change alters plant-herbivore interactions. N. Phytol. 229, 1894–1910. https://doi.org/10.1111/nph.17036.

Hanks, L.M., Denno, R.F., 1993. Natural enemies and plant water relations influence the distribution of an armoured scale insect. Ecology 74, 1081–1091. https://doi.org/10.2307/1940478.

Hanley, P.A., Arndt, S.K., Livesley, S.J., Szota, C., 2021. Relating the climate envelopes of urban tree species to their drought and thermal tolerance. Sci. Total Environ. 753, 142012 https://doi.org/10.1016/j.scitotenv.2020.142012.

Hou, Y., Li, J., Li, G., Qi, W., 2023. Negative effects of urbanization on plants: A global meta-analysis. Ecol. Evol. 13, e9894 https://doi.org/10.1002/ece3.9894.

Hudgins, E.J., Koch, F.H., Ambrose, M.J., Leung, B., 2022. Hotspots of pest-induced US urban tree death, 2020–2050. J. Appl. Ecol. 59, 1302–1312. https://doi.org/10.1111/1365-2664.14141.

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

Kim, H.H., 1992. Urban heat island. Int. J. Remote Sens. 13, 2319–2336. https://doi.org/10.1080/01431169208904271.

Klapwijk, M.J., Csóka, G., Hirka, A., Björkman, C., 2013. Forest insects and climate change: long-term trends in herbivore damage. Ecol. Evol. 3, 4183–4196. https://doi.org/10.1002/ece3.717.

Levine, J.M., D'Antonio, C.M., 1999. Elton revisited: a review of evidence linking diversity and invasibility. Oikos 87, 15–26. https://doi.org/10.2307/3546992.

Locosselli, G.M., Camargo, E.Pd, Moreira, T.C.L., Todesco, E., Andrade, Md.F., et al., 2019. The role of air pollution and climate on the growth of urban trees. Sci. Total Environ. 666, 652–661. https://doi.org/10.1016/j.scitotenv.2019.02.291.

Mastin, A.J., Gottwald, T.R., van den Bosch, F., Cunniffe, N.J., Parnell, S., 2020. Optimising risk-based surveillance for early detection of invasive plant pathogens. PLoS Biol. 18, e3000863 https://doi.org/10.1371/journal.pbio.3000863.

Mech, A.M., Tobin, P.C., Teskey, R.O., Rhea, J.R., Gandhi, K.J.K., 2018. Increases in summer temperatures decrease the survival of an invasive forest insect. Biol. Invasions 20, 365–374. https://doi.org/10.1007/s10530-017-1537-7.

Meineke, E.K., Frank, S.D., 2018. Water availability drives urban tree growth responses to herbivory and warming. J. Appl. Ecol. 55, 1701–1713. https://doi.org/10.1111/1365-2664.13130.

Meineke, E.K., Dunn, R.R., Sexton, J.O., Frank, S.D., 2013. Urban warming drives insect pest abundance on street trees. PLoS ONE 8, e59687. https://doi.org/10.1371/journal.pone.0059687.

Paap, T., Burgess, T.I., Wingfield, M.J., 2017. Urban trees: bridge-heads for forest pest invasions and sentinels for early detection. Biol. Invasions 19, 3515–3526. https://doi.org/10.1007/s10530-017-1595-x.

Parsons, S.E., Sozanski, K.S., Wilson, A.A., Frank, S.D., 2020. Effects of temperature and habitat complexity on an urban tree pest (*Tinocallis kahawaluokalani*), natural enemies, and predation services in the city. Urban Ecosyst. 23, 13–26. https://doi.org/10.1007/s11252-019-00900-7.

Raum, S., Collins, M., Urquhart, J., Potter, C., Pauleit, S., et al., 2023. Tree insect pests and pathogens: a global systematic review of their impact in urban areas. Urban Ecosyst. https://doi.org/10.1007/s11252-022-01317-5.

Raupp, M.J., Shrewsbury, P.M., Herms, D.A., 2010. Ecology of herbivorous arthropods in urban landscapes. Annu. Rev. Entomol. 55, 19–38. https://doi.org/10.1146/annurev-ento-112408-085351.

Root, R.B., 1973. Organisation of a plant-arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleracea*). Ecol. Monogr. 43, 95–124. https://doi.org/10.2307/1942161.

Salmond, J.A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., et al., 2016. Health and climate related ecosystem services provided by street trees in the urban environment. Environ. Health 15, S36. https://doi.org/10.1186/s12940-016-0103-6.

Shrewsbury, P.M., Raupp, M.J., 2006. Do top-down or bottom-up forces determine *Stephanitis pyrioides* abundance in urban landscapes? Ecol. Appl. 16, 262–272. https://doi.org/10.1890/04-1347.

Sjöman, H., Östberg, J., 2019. Vulnerability of ten major Nordic cities to potential tree losses caused by longhored beetles. Urban Ecosyst. 22, 385–395. https://doi.org/10.1007/s11252-019-0824-8.

Stamp, N., 2004. Can the growth-differentiation balance hypothesis be tested rigorously? Oikos 107, 439–448. https://doi.org/10.1111/j.0030-1299.2004.12039.x.

Stevens, R.B., 1960. Cultural practices in disease control. In: Horsfall, J.G. (Ed.), Plant pathology: an advanced treatise. Academic Press Inc,, London, United Kingdom, pp. 357–429.

Sutherland, W.J., Woodroof, H.J., 2009. The need for environmental horizon scanning. Trends Ecol. Evol. 24, 523–527. https://doi.org/10.1016/j.tree.2009.04.008.

Tabassum, S., Beaumont, L.J., Shabani, F., Staas, L., Griffiths, G., et al., 2023. Which Plant Where: a plant selection tool for changing urban climates. Arboric. Urban For. 49, 190–210. https://doi.org/10.48044/jauf.2023.014.

Tobin, P.C., Gray, D.R., Liebhold, A.M., 2014. Supraoptimal temperatures influence the range dynamics of a non-native insect. Divers. Distrib. 20, 813–823. https://doi.org/10.1111/ddi.12197.

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

Turbelin, A.J., Diagne, C., Hudgins, E.J., Moodley, D., Kourantidou, M., et al., 2022. Introduction pathways of economically costly invasive alien species. Biol. Invasions 24, 2061–2079. https://doi.org/10.1007/s10530-022-02796-5.

Yang, J., Bou-Zeid, E., 2018. Should cities embrace their heat islands as shields from extreme cold? J. Appl. Meteorol. Climatol. 57, 1309–1320. https://doi.org/10.1175/JAMC-D—17-0265.1.

Young, R.G., Milián-García, Y., Yu, J., Bullas-Appleton, E., Hanner, R.H., 2021. Biosurveillance for invasive insect pest species using an environmental DNA metabarcoding approach and a high salt trap collection fluid. Ecol. Evol. 11, 1558–1569. https://doi.org/10.1002/ece3.7113.

Zhang, J., Huang, Y., Pu, R., Gonzalez-Moreno, P., Yuan, L., Wu, K., Huang, W., 2019. Monitoring plant diseases and pests through remote sensing technology: A review. Comput. Electron. Agric. 165, 104943 https://doi.org/10.1016/j.compag.2019.104943.