Urban Ecosystems
https://doi.org/10.1007/s11252-022-01317-5

Tree insect pests and pathogens: a global systematic review of their impacts in urban areas

Susanne Raum[1,2] · C. Matilda Collins[3] · Julie Urquhart[4] · Clive Potter[3] · Stephan Pauleit[5] · Monika Egerer[5]

Accepted: 12 December 2022

Abstract

Trees contribute greatly to urban environments and human well-being, yet relatively little is known about the extent to which a rising incidence of tree insect pests and pathogens may be affecting these contributions. To address this issue, we undertook a systematic review and synthesis of the diverse global empirical evidence on the impacts of urban tree insect pests and pathogens, using bibliographic databases. Following screening and appraisal of over 3000 articles from a wide range of fields, 100 studies from 28 countries, spanning 1979–2021, were conceptually sorted into a three-part framework: (1) environmental impacts, representing 95 of the studies, including those reporting on tree damage, mortality, reduced growth, and changes in tree function; (2) social impacts were reported by 35 of studies, including on aesthetics, human health, and safety hazards; and (3) economic impacts, reported in 24 of studies, including on costs of pest management, and economic losses. There has been a considerable increase in urban impact studies since 2011. Evidence gaps exist on impacts on climate-regulating capacity, including temperature regulation, water retention, soil erosion, and wind protection, but also on specific hazards, nuisances, human well-being, property damages, and hazard liabilities. As a knowledge synthesis, this article presents the best available evidence of urban tree insect / pathogen impacts to guide policy, management and further research. It will enable us to better forecast how growing threats will affect the urban forest and plan for these eventualities.

Keywords Risk assessment · Cities · Diseases · Urban trees · Urban forests · Evidence synthesis · PRISMA · Policy

Introduction

Urban trees are a significant component of the green infrastructure of many towns and cities around the globe (Pearlmutter et al. 2017) and are among the most prominent natural features from both visual and functional perspectives (Wolf et al. 2020). In addition to their contribution to biodiversity (Threlfall et al. 2017), urban trees can remove certain air pollutants (Bottalico et al. 2017), reduce the severity of urban flooding (Berland et al. 2017), contribute to urban residents' wellbeing (Pearlmutter et al. 2017), provide recreational opportunities (Jennings et al. 2016), and are valued landscape features (Price 2003). Urban forest canopy cover (i.e., all trees within an urban area) is also vitally important to adapt to rising temperatures (Rahman et al. 2020), as trees can provide substantial cooling effects (Werbin et al. 2020). Because of these important contributions, cities worldwide (e.g., Beijing, New York, Porto, Singapore) are investing resources to maintain existing trees and to expand current tree canopy cover (Campbell 2014; Pinto et al. 2016; Yao et al. 2019; Turrell 2020).

Cities, however, can present a challenging environment for trees (Pauleit et al. 2002). Urban trees are typically

✉ Susanne Raum
susanne.raum@tum.de

C. Matilda Collins
t.collins@imperial.ac.uk

Julie Urquhart
jurquhart1@glos.ac.uk

Clive Potter
c.potter@imperial.ac.uk

Stephan Pauleit
pauleit@tum.de

Monika Egerer
monika.egerer@tum.de

1 Strategic Landscape Planning and Management, Technical University Munich, Munich, Germany

2 Centre for Environmental Policy, Imperial College London, London, UK

3 Imperial College London, London, UK

4 University of Gloucestershire, Cheltenham, UK

5 Technical University Munich, Munich, Germany

Published online: 20 February 2023

exposed to greater extremes and variability of biophysical stresses than trees in rural environments; this includes pollution, mechanical damage and impeded access to water (Malthus et al. 2000). They are also threatened by rising incidences of biotic and non-biotic disturbances, including pests and diseases, storms, droughts, high temperatures, and fire (Referowska-Chodak 2019). Insect pests, fungal pathogens, high temperatures, and drought are currently amongst the greatest disturbance threats to urban trees (Ordóñez and Duinker 2015; Rötzer et al. 2021).

Tree insect pest and fungal pathogen (hereafter insects / pathogens) outbreaks, especially, have already led to large-scale tree losses for many towns and cities (Sjöman and Östberg 2019) and are the principal focus of this review. These may be native or non-native tree insects / pathogens. Prominent examples are the dangerous Asian longhorned beetle (*Anoplophora glabripennis*) (Haack et al. 1997) and the Emerald ash borer *(Agrilus planipennis)* (Herms and McCullough 2014) and the lethal fungal pathogens Dutch elm disease *(Ophiostoma novo-ulmi*) (Lanier et al. 1988) and Chalara ash dieback *(Hymenoscyphus fraxineus)* (Heuch 2014). Insects / pathogens may affect urban trees through defoliation, staining, boring, and loss of branches or a combination of these; they may also cause tree mortality and have negative impacts on human health and visual aesthetics (Boyd et al. 2013; NASEM 2019). Insects / pathogens may also affect the ability of trees to contribute to climate mitigation and adaptation, especially their capacity to cool the urban temperature, and their ability to help mitigate against air pollution, landslides, and flooding (Anderegg et al. 2020).

International trade, human movement and climate change will likely further increase the risks posed by tree insects / pathogens (Potter and Urquhart 2017; Pyšek et al. 2020; Tubby and Webber 2010). Transport hubs and the wide range of potential host trees in streets, gardens, and parks, can be particularly vulnerable to the introduction of non-native tree insects / pathogens in urban areas (Branco et al. 2019). The biosecurity threat of introduced tree insects / pathogens, especially in combination with increasing heat and drought, represents a growing challenge to contemporary urban tree management, especially in terms of human and financial resources (Cregg and Dix 2001; Tomlinson et al. 2015). Many local authorities do not have the budget to manage green space effectively and remove diseased or dead trees which leads to an overall reduction of tree canopy cover (Fletcher and Collins 2020). This situation points to the urgent need to increase the awareness of these threats and to develop new tree management strategies that take these multiple risks into account (Ordóñez and Duinker 2015). The cumulative and mounting pressures of these threats also highlight a need for municipal green space managers (and other tree owners / managers) to incorporate effective measures that increase the resilience of the urban forest to multiple risks (McPherson and Kotow 2013; Wyse et al. 2015).

The development of successful new urban tree policies and practical management measures not only requires a better understanding of the causes and types of tree insects / pathogens infestations in urban areas, but also assessments of the extent of the damage, their social-, economic-, and environmental impacts, and hidden or potential impacts. Currently, this information is derived from a fragmented evidence base, drawing on experience from a range of case studies across different fields. Several comprehensive reviews, for instance, examined the threats of tree insect / pathogen outbreaks (e.g., Boyd et al. 2013; Freer-Smith and Webber 2015; Graziosi et al. 2019; Hlásny et al. 2021; Tubby and Webber 2010) and forest insect eradication measures (e.g., Brockerhoff et al. 2010) or the interactions between tree insect pests and other disturbances (e.g., Canelles et al. 2021; Dale et al. 2001; Temperli et al. 2013). However, most of these focus on forests in the wider environment, with a focus on the impacts of individual tree insects / pathogens on the structural and functional components of the affected forest environments (e.g., Bearup et al. 2014; Carnegie et al. 2016; Fukasawa and Seiwa 2016). Others investigated the economic costs of tree insect or pathogen outbreaks, especially due to loss of timber (e.g., Aukema et al. 2011; Ayres and Lombardero 2000; Hill et al. 2019) or fruit tree products (e.g., Alvarez et al. 2016; Cambra et al. 2006; Hadidi et al. 2017). To our knowledge, none of these studies assesses the socio-economic and environmental impacts concurrently and in an urban context. A thorough assessment and quantification of tree insect / pathogen impacts in urban contexts, however, is a key prerequisite for forward looking planning and better management of the tree resource in our towns and cities (Referowska-Chodak 2019).

This systematic review responds to this need, drawing together the available evidence across a diverse published literature on tree insect pests and pathogens from cities around the globe, while also identifying research gaps that need filling. We aim to answer the following primary question: (1) what are the (quantifiable) impacts of tree insect pests and pathogen outbreaks in urban areas? Furthermore, we ask: (2) which insects / pathogens cause damage to urban trees, to which species and to what extent? And (3) which lessons regarding urban tree policies and management practice can be derived? Framed as a knowledge synthesis, this article presents the best available evidence of urban tree insect / pathogen impacts and forecast potential threats to inform policy, management, and further research. We also discuss the implications of our findings, as well as their limitations.

Methods

Literature review approach

We used a systematic review approach (Moher et al. 2009) to assess the literature on urban tree insects / pathogens. This type of literature review 'attempts to collate all empirical evidence that fits pre-specified eligibility criteria in order to answer a specific research question' (Higgins et al. 2019:1). Systematic 'narrative' reviews are particularly appropriate when a literature review is conducted with a collection of studies that have used diverse methodologies and cannot be aggregated together in a traditional statistical (meta-) analysis (Ryan and Cochrane Consumers and Communication Review Group 2013). The review followed established procedures and reporting standards (Preferred Reporting Items for Systematic Reviews and Meta-Analysis—PRISMA) (Page et al. 2021a, b) which enabled us to develop a strict protocol a priori for searching and selecting articles (Supplementary Information SI1), whilst minimising bias. The PRISMA procedure is one of the most widely used across the research spectrum (Siddaway et al. 2019).

For the purpose of this review, we included all tree typologies occurring in urban areas, from single trees to forests in both public and private spaces (Ordóñez and Duinker 2015). Collectively these are often defined as the 'urban forest' (Konijnendijk et al. 2006). The urban forest consists of complex interactions between nature and people (Ordóñez and Duinker 2015). Thus, we present the impacts of tree insects / pathogens in a three-part framework: ecological / environmental, socio-cultural, and economic. The focus of our review were specifically the reported negative impacts as these, arguably, have more consequences for policy and practice.

Study selection

The search aimed to capture the available scientific evidence (quantitative and qualitative) relevant to the research question(s). Reflecting the multi-disciplinarity of the relevant body of publications, studies were selected using the academic databases Scopus, Web of Science (Core Collection) and Science Direct to capture a spectrum of both the natural and social science literature. The scope of the review was geographically international, though restricted to peer-reviewed research articles, excluding book chapters, conference papers, or other grey literature. No language limits were placed on the search to allow for the capture of relevant foreign language studies with English abstracts. The final analysis, however, was limited to articles available in English. Similarly, our search assigned no specific time range, although earlier literature is less likely to be catalogued or available electronically and this may introduce some bias.

The following four main search term strings and their keywords were used for the bibliographic database searches: 1) urban OR city OR cities OR town*OR peri-urban OR suburban OR metropol*; 2) tree* OR forest*OR street tree* OR canop*; 3) pest OR pests OR insect* OR disease* OR pathogen*; 4) impact* OR effect* OR risk* OR threat* OR mortal* OR damage*. These were derived from scoping searches in Google Scholar, through a reading of the identified literature, and through discussion with other members of the study team and the University's specialist librarians. They were further refined during scoping database searches to ensure that key articles identified beforehand were meeting the criteria used in the search. To avoid subjective or purposeful selection of articles, a frequent problem in literature reviews (Haddaway et al. 2015), specific criteria were used in addition to the above keywords to determine the inclusion or exclusion of articles.

Specific criteria included: (1) the article must be available in Scopus, Web of Science Core Collection, or Science Direct; (2) it must be original peer-reviewed research; (3) the full article must be available electronically; (4) the full article must be available in English; (5) the title or abstract must contain one of the above 4 keyword terms or a common or Latin name of these (i.e. city, tree, insect, and pathogen common or Latin names); and (6) the results must contain information on impacts of tree insects / pathogens in urban areas. We included review articles in the database search as scoping database searches revealed that empirical articles were occasionally wrongly attributed as review articles. The full search strings are shown in Supplementary Information SI2, Table 1.

7 cities (US)The documents resulting from the final search (November 2021), were imported into Covidence (https://www.covidence.org), via the reference management software EndNote 20, and then screened in two phases: 1) title / abstract screening and 2) full text screening. The use of Covidence, a web platform for managing the literature screening process endorsed by the renowned international Cochrane collaboration for systematic reviews, had the advantage of simplifying whilst also systemising the approach (Harrison et al. 2020). The aforementioned specific set of criteria was used for each of the two screening phases to assess the relevance of the articles and determine their inclusion or exclusion from the synthesis (Supplementary Information SI2, Table 2).

To confirm screening quality and consistency, two researchers independently conducted a test screening round of 50 articles each during both screening phases, for which multirater kappa statistic (Randolph 2008) was found to be substantial ($K = 0.75$, $p < 0.0001$).) In both

Table 1 The impacts of urban tree insects / pathogens reported in the different studies

Ecological / Environmental impacts (95 studies)	Social / Cultural impacts (35 studies)	Economic impacts (24 studies)
• Tree damages (87)	• Reduced aesthetic value (15)	• Pest management costs (15)
• Tree mortality (49)	• Human health impact (11)	• Economic losses (4)
• Reduced tree growth (8)	• Hazards, affecting human safety (8)	• Structural damage (2)
• Changes in tree function (6)	• Loss of cultural / heritage value (3)	• Loss in ornamental value (2)
• Weakened / stressed tree (5)	• Nuisance due to larvae / litter (3)	• Loss of property value (2)
• Changes in soil composition (4)	• Impact on tourism (2)	• Human health related costs (1)
• Changes in ecosystem services (3)	• Changes in sound / noise level (1)	• Changes in fibre availability (1)
• Indirect tree damage (due to predators of beetle larvae) (2)	• Changes in crime rates (1)	
• Loss of tree canopy cover (1)	• Reduced thermal comfort (1)	
• Changes in biodiversity (1)	• Pest management action affects (1)	
	• Alteration of agroecosystem (1)	

rounds, any disagreements in screening decisions were resolved through discussion and consensus. The quality of the studies was solely determined due to them being obtained from established academic databases and having been published in peer-reviewed academic journals; no other criteria were used for the purpose of this review. The study selection process is shown in a PRISMA diagram (Fig. 1).

A total of 4,431 articles were initially retrieved and this was reduced to 3,146 entries following automatic duplicate

Table 2 Representative selection (These seek to best reflect the characteristics of the array of quantified impacts across a geographical and temporal range) of the quantified ecological/environmental (env), socio/cultural (soc) and economic (econ) impacts of urban tree insects – beetles (Coleoptera)

Insect pest	Impact	Impact description	Quantification of impact	Study location	References
Ambrosia beetle *(Euwallacea interjectus)*	Env	Tree damage Tree mortality	16.22% (16.95 ha) a limited number (poplar)	Shanghai (CN)	Wang et al. (2021)
Asian long-horned beetle *(Anoplophora glabripennis)*	Env	Potential canopy loss Potential tree mortality	13—68% 30.3% (1.2 billion)	9 major cities (US)	Nowak et al. (2001)
	Econ	Potential tree removal & replacement costs Estimated tree value loss	CAD $8.6—$12.2 billion $72 million—$2.3 billion (per city)	Eastern cities (CA) 9 major cities (US)	Pedlar et al. (2019) Nowak et al. (2001)
Emerald ash borer *(Agrilus planipennis)*	Env	Ash bark loss Scaffold crack Branch fracture Exit holes Tree mortality Changes CNP & evapotranspiration flux rates Risk of provisioning services loss Risk of regulating services loss Risk of biodiversity loss	2.7% 2.5% 1.5% in 22 out of 250 trees (area A); 6 in 11 trees (area B) almost 100% (ash) 4.5%—7.8% 0.039—0.104 0.05—0.11 0.036—0.148	7 cities (US) Tver (RU) 12 cities (RU) Minneapolis, St Paul (US) All cities (US, CA, RU)	Persad and Tobin (2015) Peregudova (2019) Orlova-Bienkowskaja (2013) Fissore et al. (2012) Schrader et al. (2021)
	Soc	Risk of ornamental loss	0.19—0.49	All cities (US, CA, RU)	Schrader et al. (2021)
	Econ	Potential tree removal costs Potential tree replacement costs Potential aesthetic value loss Estimated economic costs	$2,991—$5,804 million $2.7—$5.2 million $7.7—$15 billion CAD $524—$890 million	4 states (US) All cities (CA)	Sydnor et al. (2011) McKenney et al. (2012)
Yellow beetle *(Costalimaita ferruginea)*	Env	Leaf damage	80—100% (eucalyptus)	4 cities (BR)	Dias et al. (2017)
Tiger longicorn beetle *(Xylotrechus chinensis)*	Env	Tree damage Tree loss	438 trees (mulberry) 98 trees	Barberà del Vallès (ES)	Monteys et al. (2021)

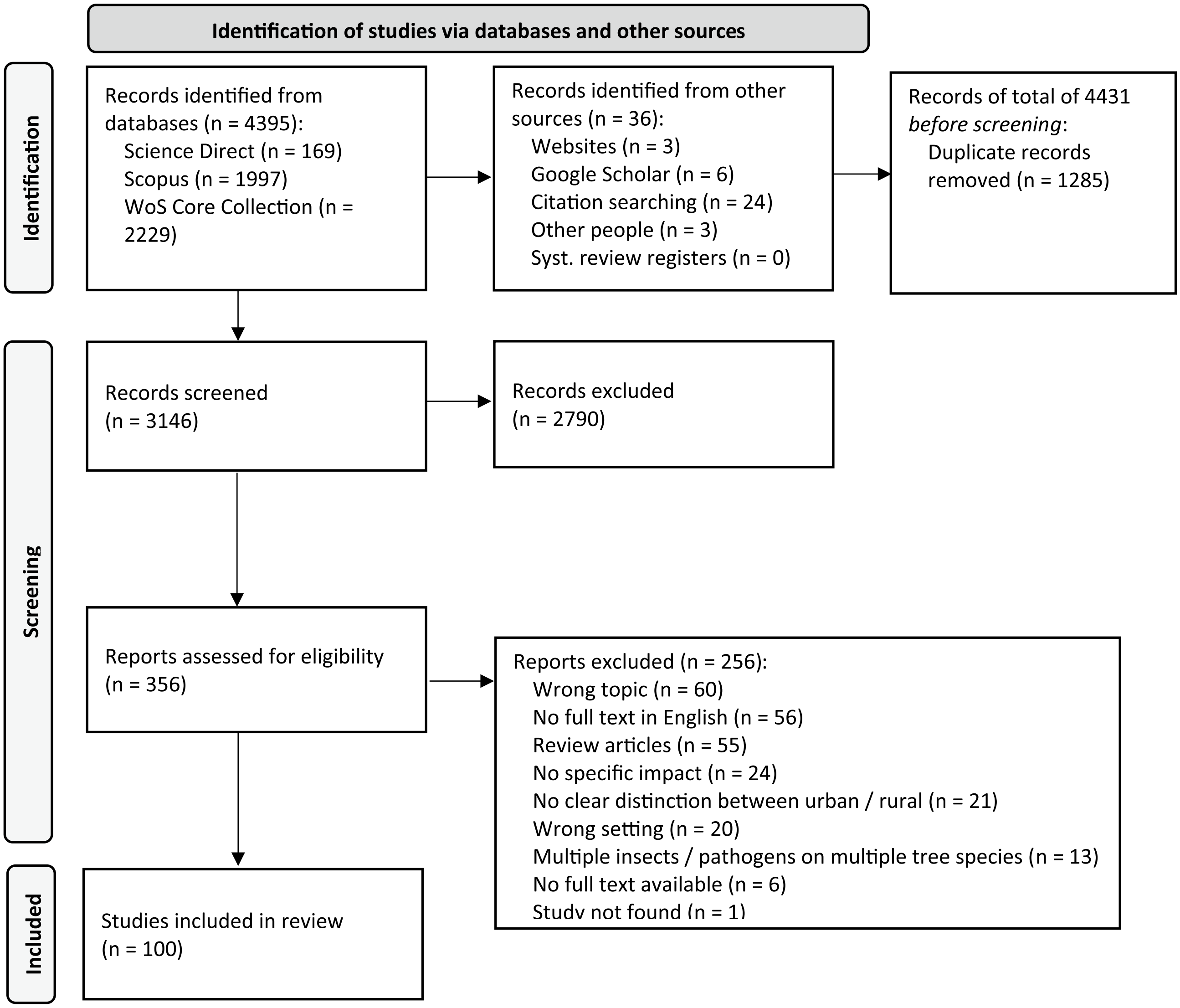


Fig. 1 Adapted PRISMA 2020 flow diagram for the systematic review process (Page et al. 2021a)

removal within Covidence. Title-abstract screening identified 356 articles for full text screening during which a total of 256 articles were excluded as they did not meet the inclusion criteria (Fig. 1). A full list of included and excluded references is shown in Supplementary Information SI3 and SI4. 59 non-English studies successfully passed the title and abstract screening. Although few of these were included in the final synthesis as no full English texts were available, they are listed with their full title in the list of excluded articles.

We only included empirical studies with a specific reference to impacts associated with urban tree insect / pathogen outbreaks. These include studies reporting information on impacts obtained through observational surveys alongside other empirical examinations. Thus, studies examining, for instance, the abundance or distribution of insect / pathogen species without any implicit consideration of impacts were excluded. For example, Baumgartner and Rizzo's (2001) study on the distribution of Armillaria species in California or Chung et al.'s (2015) work on the dissemination pattern of brown root rot disease in Taiwan did not examine impacts. Neither did we consider studies which examined tree insects or pathogens generically without clearly differentiating between rural and urban areas, such as Donovan et al.'s (2013) study on human health and the spread of the emerald ash borer. We also excluded studies, investigating multiple insects / pathogens on multiple tree species in parallel because we could not derive information on respective impacts from individual insects / pathogens. Exceptions were studies reporting on associated insects / pathogens, such as ‘elm bark beetles’ and the invasive fungal pathogen ‘*Ophiostoma (novo) ulmi*’ (e.g., Miyamoto et al. 2019; Jürisoo et al. 2019). Still, despite a strict adherence to the a priori in- and exclusion criteria, some judgment in drawing the line was needed at times. Six studies (Hesler et al. 1999; Annesi et al. 2003; Izhevskii and Mozolevskaya 2010; Grasso et al. 2012; Griffin 2015; Koukol et al. 2015) were included although they only matched 3 of the 4 keyword category terms as they fully matched all other inclusion criteria; they did mention synonyms for impacts not listed in our list of keywords.

Data extraction and systematisation

Selected articles were exported in CSV format with their bibliographic information to MAXQDA (a software for qualitative data analysis). The full texts of the selected research articles were then deductively coded, using the three-part framework and a set of predetermined parameters (Supplementary Information SI2, Table 3) which were informed by the review questions. For each article, we recorded the following information: 1) bibliographic information; 2) information relating to the inclusion criteria; and 3) information relating to the study itself (for full details see Supplementary Information SI2, Table 3). This common analysis scheme was applied to all the reviewed articles. The data were extracted to an Excel spreadsheet (Supplementary Data).

Data analysis and synthesis

For data analysis, we used descriptive statistical (Myers et al. 2010) and narrative synthesis approaches (Lisy and Porritt 2016; Ryan and CCCRG 2013). The former includes spatial–temporal comparisons, as well as exploration of patterns and variances in the data (Myers et al. 2010), the latter, a qualitative narrative analysis (Ryan and CCCRG 2013). First, the studies were classified according to the number of countries that reported impacts, and the occurrences of a specific impact type to identify trends. We used a generalized linear model to explore whether the relative proportions of each category of impact changed with time. The model was fit with a quasi-poisson distribution as the response variable, number of papers in any year was overdispersed. We then summed the occurrences of a specific insect type, pathogen and tree species involved. Next, we used a qualitative approach to analyse and synthesise (Lisy and Porritt 2016; Ryan and CCCRG 2013) the impacts of insects / pathogens in urban areas, using first an inductive approach to classify the studies in this review, and then a deductive approach to fit the themes extracted from the studies into the predetermined three-part framework: ecological / environmental, social / cultural, and economic impacts. This approach is useful to summarise very heterogeneous and often unbalanced data across studies (Ryan and CCCRG 2013). We summarised the available quantitative impacts by types of tree insects / pathogens.

Results of the systematic literature review on the impacts of urban tree insect pests / pathogens

General overview of selected articles

The 100 peer-reviewed articles reporting impacts of tree insects /pathogens selected for detailed review were published between 1976 and November 2021 and represent research conducted in urban and peri-urban fringe settings around the globe. The articles capture a wide range of impacts caused by an equally wide range of tree insects / pathogens in 28 different countries: 2 Northern American countries, 17 European countries, and 9 countries from other continents. One of the articles (Schrader et al. 2021) covered multiple cities in three different countries (Canada, USA, Russia). Almost half of the studies (47) were conducted in Europe, with 10 alone in Italy, followed by Western Russia[1] with 8 and the Czech Republic with 4 studies. Notably, 26 studies were conducted in Eastern European countries. Thirty-six percent of studies were conducted in North America, with 29 studies from the USA and 7 from Canada. The remaining 19% of the studies were conducted in Asia (7), South America (6), Africa (4), and Oceania (2) (Fig. 2).

Over the last decade, there has been a steady rise in the number of articles published on the impacts of tree pests / pathogens in urban areas (Fig. 3). Early peer reviewed studies were exclusively North American or European in focus. The number of studies related to urban tree insects / pathogens has increased since 2011, including from non-European and non-Northern American countries. Of the 100 articles included in this systematic review, 77% were published since 2011 (Fig. 3).

There has been a steady increase in studies of all three impact types, especially for those reporting ecological / environmental (Fig. 4). Most studies reporting on social and economic impacts also report on environmental impacts, but not the other way round. Not all studies focused primarily on one or several of our three impact types; several reported on these alongside another line of investigation. There was no evidence in these data that the proportions varied with time ($F = 0.17$, $d.f. = 2,60$, $p = 0.84$) and thus that the relative importance of each category in the academic literature has

[1] Please note that the Russian studies were undertaken in the European part of Russia.

Table 3 Representative selection of the quantified ecological/environmental (env), socio/cultural (soc) and economic (econ) impacts of other urban tree insects

Insect pest	Impact	Impact description	Quantification of impact	Study location	References
Horse chestnut leafminer *(Cameraria ohridella)*	Env	Foliar damage Cytoplasmic peroxidase activity	50—80% 2.1-fold increase	Szczecin (PL) Dnipro (UA)	Dzięgielewska et al. (2017) Seliutina et al. (2020)
European gipsy moth *(Lymantria dispar)*	Env	Potential Defoliation Potential tree mortality Potential carbon storage loss	4—36% 17,000—275,000 trees 18,667—1083Mt	Baltimore (US)	Bigsby et al. (2014)
	Soc	Itchy skin rashes risk Estimated human health risk	1.6—10.4% 11,275 (1.8%)—40,832 people (6.4%)	Lunenburg, Medway (US) Baltimore (US)	Tuthill et al. (1984) Bigsby et al. (2014)
	Econ	Estimated human health treatment costs Insect suppression cost Host tree removal Tree replacement costs Treatment material Support and overhead Egg mass survey Loss of air pollution removal benefits	$0.054—$0.196 million $0—$0.269 million $1.502—$24.060 million $1.738—$26.022 million $8.95/ha $25.24/ha $24.68 per 0.01/ha $1.365—$7.407 million	Baltimore (US) Sub-urban parks in Maryland (US) Baltimore (US)	Bigsby et al. (2014) Straka et al. (1997) Bigsby et al. (2014)
Pine processionary moth *(Thaumetopoea pityocampa)*	Soc	Cutaneous reactions	114 (14%) people	Valladolid (ES)	Vega et al. (2011)
Oak processionary moth *(Thaumetopoea processionea)*	Soc	Cutaneous reactions	57 (5.6%) people	Vienna (AT)	Maier et al. (2003)
Black sawfly *(Tomostethus nigritus)*	Env	Defoliation	43—95.8% (ash)	Kharkiv (UA)	Meshkova et al. (2017)
Sawfly *(F.pumila, H. nemoratus, P. thomsoni)*	Env	Defoliation	32,000ac (birch)	Anchorage, Fairbanks (US)	Snyder et al. (2007)
Mealybug *(Praelongorthezia praelonga)*	Env	Tree damage Tree mortality	5.8—11.8% 5.8%	Montes Claros (BR)	Lemes et al. (2019)
Asian sub-terranean termite *(Coptotermes gestroi)*	Env	Tree damage Tree mortality	on 58% of trees 25 trees	Fort Lauderdale (US)	Chouvenc and Foley (2018)
Wasp *(Megastigmus transvaalensis)*	Env	Drupe damage	1—55% (peppertree)	Sorocaba (BR)	Ferreira-Filho (2015)
Red palm weevil *(Rhynchophorus ferrugineus)*	Env	Tree mortality	25% (palm)	Bari (IT)	Sardaro et al. (2018)
	Soc	Ornamental value loss	€2—2.5 million	Bari (IT)	Sardaro et al. (2018)
	Econ	Tree removal costs	€2.1—2.6 million	Bari (IT)	Sardaro et al. (2018)
Beech leaf-mining weevil *(Orchestes fagi)*	Env	Tree mortality	32%—44%	Halifax (CA)	Sweeney et al. (2020)
	Econ	Tree removal costs	$474 ± 66 (per tree) $1934 ± 451 (per resident)	Halifax (CA)	Sweeney et al. (2020)
Hemlock woolly adelgid *(Adelges tsugae)*	Env	Reduced mechanical strength & flexibility in twigs	25%	Medford (US)	Soltis et al. (2014)

changed within this time window. As expected, the model supported that the number of articles on the topic has risen during this window (F = 44, d.f. = 1,62, $p < 0.001$) and that the proportions of each category are not the same (F = 20, d.f. = 2,62, $p < 0.001$).

Tree insect / pathogens and their impacts in urban areas

The majority (73) of studies addressed impacts of insect infestations and approximately one third (39) of pathogens.

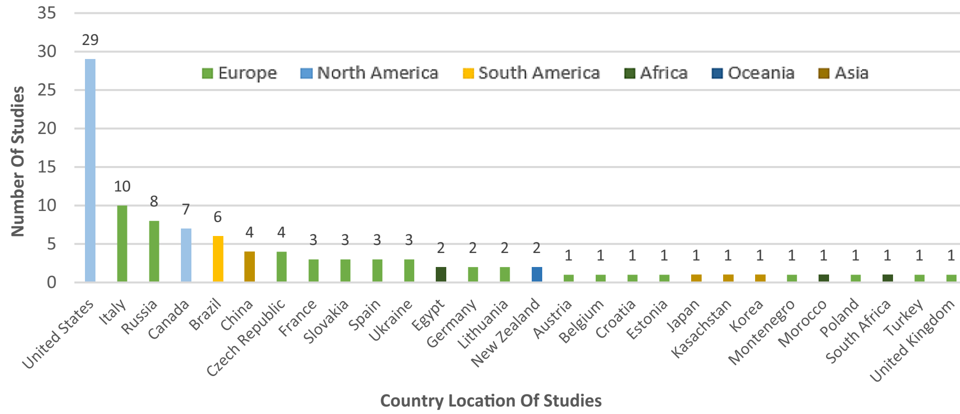


Fig. 2 The number of reviewed studies on urban tree insects / pathogens per country ($n = 100$)

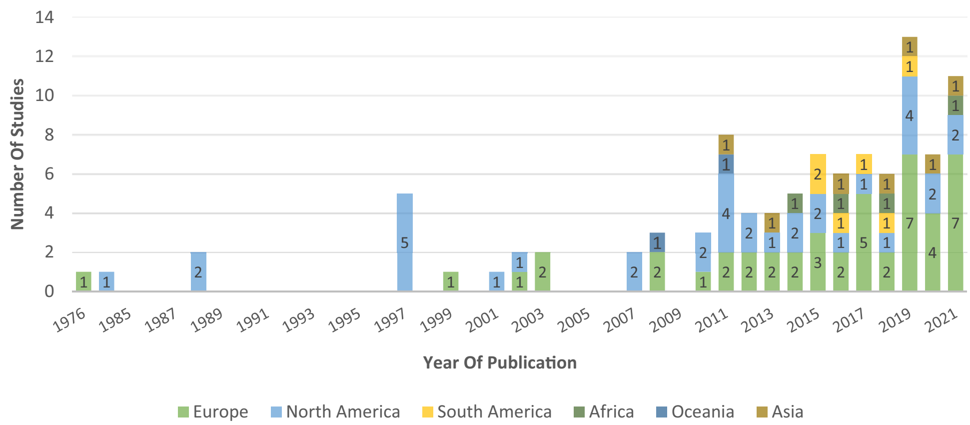


Fig. 3 The number of studies on urban tree insects / pathogens according to continent and year of publication ($n = 100$). Data collected for the year 2021 ended in mid-November

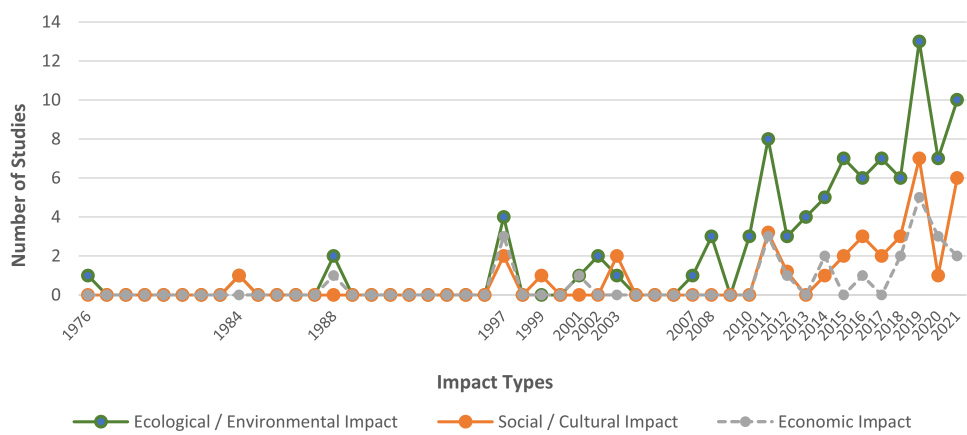


Fig. 4 Trends in studies ($n = 100$) covering ecological / environmental, social / cultural, and economic impacts. Data collected for the year 2021 ended in mid-November

Amongst the insects, most concerned beetles (Coleoptera) (35) and moths (Lepidoptera) (20), whereas pathogen-related studies were dominated by fungi (38) with only one on bacteria. The impacts of spider mites were reported in two studies, although, strictly speaking, these are not insects. Other reported insects were aphids, cicada, leafhoppers, lice (Hemiptera) (7), sawflies, wasps (Hymenoptera) (4), and termites (Isoptera) (3). Twelve studies on impacts examined both insects and fungal pathogens. This included studies on Ophiostoma novo-ulmi, a pathogen distributed by elm bark beetles (4) and horse chestnut leaf miners and leaf blotch disease (4) often cumulatively impacting tree health.

Over half of the beetle-related studies concerned the emerald ash borer (USA = 10; Russia = 6; Canada = 1)[2] and

[2] One study investigated the emerald ash borer in Russia, Canada and the US.

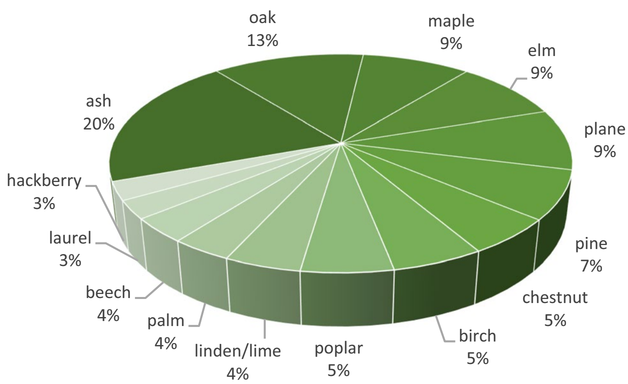


Fig. 5 The percentage occurrence of the principal tree species reported in the selected studies

the Asian longhorned beetle (USA = 2; Canada = 1). Specific urban impacts of the horse chestnut leaf miner moth were investigated in four countries (Czech Republic, Lithuania, Poland, and Ukraine); the impacts of European gipsy moths were studied in the USA (5), of oak processionary moths in Central Europe (3) and pine processionary moths in southern Europe (3). Dutch elm disease (4) and canker stain disease (3) were the most studied fungi. The impacts of the former were examined in Estonia, Japan, Russia, and the USA, and of the latter in France, Turkey, and the USA. Most studies involved only one tree species; ten involved more than one tree species (Fig. 5).

The studies reported a wide range of different ecological / environmental, social / cultural, and economic impacts caused by tree insects / pathogens in urban contexts (Table 1). Not all studies, however, provided quantitative data on impacts. For those which did, limited or incomplete documentation of temporal and spatial scales impeded robust comparison across studies on the same impacts. Moreover, the studies used a wide range of variance types/units of measurement, ranging from counts and percentages, to dollar values and areas. Some used total values, others per area, per tree, per hour as well as actual, potential or estimate values (Supplementary Information SI5).

Ecological / environmental impacts

Ecological / environmental impacts were reported in 95% of the studies. The main impacts were tree damages (87), involving leaves, branches, or the trunks of trees and tree loss (49), either due to tree mortality caused directly by the insects / pathogens or due to pre-emptive removal of diseased trees. Tree damages ranged from changes in colour / discolouration (39), dieback (33), defoliation (30), lesions / cankers (19), larval galleries (16), wilting / withering (14), exit holes (11), epicormics shoots (5), exudations (3), deformity (2), chlorosis (2), sooty mould over leaves (1), swellings (1) and brownish moist (1). Further ecological / environmental impacts included reduced growth of leaves, buds, and trees (8) and changes in tree function (6), such as changes in biomechanical function (2), biogeochemical and hydrological function (1), carbon sequestration capacity (1), air pollution removal capacity (1), and their overall functional state (1). Other impacts included trees being weakened or stressed due to insects / pathogens (5), changes in the composition of the soil around/beneath the affected trees (4), indirect tree damage due to woodpeckers, attempting to access beetle larvae in the tree trunk (2), loss of urban tree canopy cover (1), changes in ecosystem services provisioning (3), and changes in associated biodiversity due to changes in bird species composition (1) (Supplementary Data). In all, 72 studies provided quantified values of the urban tree insect / pathogen impacts identified (Tables 2, 3, and 4).

Social / cultural impacts

Thirty-five studies reported one, or several, socio-cultural impacts, the main ones being reduced aesthetic / landscape or ornamental value (15), health impacts to people due to allergic reactions (11), and hazard to people, affecting human safety (8). Aesthetic impacts mentioned were diverse and attributed to defoliation and discolouration of leaves, wilting, sanitary branch or tree removal, or tree mortality. Impacts on human health, due to exposure to setae of various caterpillar species living on trees, range from pruritus, weal and flare, persistent itchy papules/dermatitis, conjunctivitis, pharyngitis, and respiratory distress. Such health impacts were reported in association with oak processionary moths (3), pine processionary moths (3), and European gipsy moths (3). Although hazards, affecting human safety due to falling branches or trees were reported in 8 studies, none of these provided quantitative data (Supplementary Data). Thirteen studies provided a quantification of social / cultural impacts (Tables 2, 3, and 4).

Economic impacts

Twenty-four studies reported one or several economic impacts and / or estimates of the potential costs caused by tree insects / pathogens in urban areas. The majority of these examined pest management costs (15), including treatment costs, tree removal and replacement costs, and community overhead costs (i.e., costs of staff time to manage responses, monitoring-, surveillance-, and communication costs). Others examined economic losses (4), including to the food industry and in nursery production, as well as damage costs to adjacent structures, especially wooden structures (2), loss in ornamental / landscape value (2), negative impacts on

Table 4 Representative selection of the quantified ecological/environmental (env), socio/cultural (soc) and economic (econ) impacts of urban tree pathogens (fungi)

Pathogen	Impact	Impact description	Quantification of impact	Study location	References
Ash dieback *(Hymenoscyphus fraxineus)*	Env	Tree damage Tree mortality	70% (ash) 1%	Leipzig (DE)	Volke et al. (2019)
Dutch elm disease *(Ophiostoma novo-ulmi)*	Env	Tree damage Tree mortality	7 of 471 (elm) 7 of 471	Sapporo (JP)	Miyamoto et al. (2019)
	Econ	Tree removal costs	≥ $500 (per tree)	Syracuse (US)	Bukowski (2019)
Canker stain disease *(Ceratocystis platani)*	Env	Tree damage Tree mortality	26.5% (plane) 5.6% (plane)	Istanbul (TR)	Lehtijärvi et al. (2018)
	Econ	Tree treatment costs	$34.65 (per tree)	Modesto (US)	Perry and McCain (1988)
Canker dieback *(Diaporthe scabra)*	Env	Tree cankers Tree mortality	10—30 cm 20 of 50 (plane)	Catania (IT)	Grasso et al. (2012)
Horse-chestnut leaf blotch *(Guignardia aesculi)*	Env	Leaf area destroyed	2.75%	Ceské Budejovice (CZ)	Kopačka et al. (2021)
Pine wood nematode *(Bursaphelenchus xylophilus)*	Env	Changes in C + N levels in litterfall	50 – 86% variation	Jinju (KR)	Kim et al. (2011)
Sudden oak death *(Phytophthora ramorum)*	Env	Pest management costs Loss of property value	$7.5 million $135 million	Californian cities (US)	Kovacs et al. (2010)
White rot fungus *(Inonotus rickii)*	Env	Reduced density & axial compression strength	7—16% (box elder) 11- 21%	Rome (IT)	Annesi et al. (2015)
Oak wilt *(Ceratocystis fagacearum)*	Env	Tree removal costs Potential removal & replacement costs	$18–60 million CAD$266—$420 million	Minneapolis-St Paul (US) Major cities (CA)	Haight et al. (2011) Pedlar et al. (2020)

residential property values, especially due to tree mortality (2), human health related medical costs (1), and changes in the availability of wood fibre (1) (Supplementary Data). Seventeen of these studies provided quantitative values (Supplementary Data) (Tables 2, 3, and 4).

Narrative synthesis

Of the 95 studies reporting *ecological / environmental impacts,* the majority were related to various tree damages and tree mortality. Dzięgielewska et al. (2017), for instance, reported considerable foliar damage of chestnut trees due to horse chestnut leaf miner infestation (50–80%), markedly reducing the photosynthesis area of the infected trees which may subsequently weaken them. Cumulative defoliation over several years, for instance due to European Gipsy moths has even been associated with tree mortality (Bigsby et al. 2014). The functional state of trees may also be compromised by tree insects. Horse chestnut leaf miners, for instance, have resulted in a 2.1-fold increase in cytoplasmic peroxidase activity (Seliutina et al. 2020). Miller (1997) found that twigs weakened by ovipositional wound damage in urban forests due to cicadas are more likely to die later in the summer and break during windstorms, littering the ground. Of the 49 studies reporting on tree mortality, Dutch elm disease in combination with elm yellow disease led to an almost complete loss of the American elm tree species in the US city of Syracuse (Lanier et al. 1988). Starting with an article on New York's ‘battle’ with the ‘deadly’ Asian long-horned beetle (Haack et al. 1997), we observed a steady growth in studies of introduced beetle species, especially in the US and Europe (including Western Russia), with potential to cause widespread tree mortality. In Moscow and the area immediately surrounding the city (Moscow Oblast), for instance, the emerald ash borer has killed around 1 million ash trees, although the exact figure will never be known (Straw et al. 2013).

Koenig et al. (2013), on the other hand, found changes in associated bird diversity due to ash mortality caused by the emerald ash borer in the US city of Detroit. There, the composition of woodpecker species changed: red-bellied woodpeckers and white breasted nuthatches increased, whereas both downy woodpeckers and hairy woodpeckers initially decreased, but later increased. Several studies also reported a greater intensity of insect / pathogens in street trees compared to recreational areas (e.g., Stravinskienė et al. 2015; Dzięgielewska et al. 2017). Others' report a dependence between disease outbreaks and the pre-existence of wounds both above and below ground (e.g., Zorzenon and Campos 2015; Annesi et al. 2003) or meteorological conditions;

dry or wet and warm summers making insect / pathogen outbreaks more likely or stronger (e.g., Lemes et al. 2019; Stravinskienė et al. 2015). Younger, more recently planted trees, especially when planted on poor, dry sites, appeared to be particularly vulnerable (e.g., Volkovitsh et al. 2021; Straw et al. 2013). Several pathogens were also suspected to have been transmitted through roots or even through urban waterways (e.g., Haight et al. 2011; Lehtijärvi et al. 2018).

The majority of *social / cultural studies* were related to the loss of aesthetic / ornamental value, hazards and human health impacts. In Kénitra in Morocco, for instance, the psyllid *Macrohomotoma gladiate* causes considerable unsightly damages to leaves and twigs of the widely grown Indian laurel figs which may, eventually, make them undesirable as an urban ornamental tree in Morocco (Afechtal et al. 2021). In the prominent Petrodvorets District of St. Petersburg in Russia, emerald ash borer infestation induced tree mortality directly endangers the unique palace and park ensembles of Peterhof and Oranienburg, a famous UNESCO World Heritage site (Volkovitsh et al. (2021). Outbreaks of ash sawflies in the Belgium city of Ghent not only caused leaf damage and defoliation in ash trees, but also nuisances. A lamppost positioned next to the tree was visited by hundreds of larvae. Similarly visited were a bench and a signpost (Verheyde and Sioen 2019). Various allergic reactions due to exposure to caterpillar setae associated with urban trees have become an increasing public health problem in different parts of the world. These are not only caused through direct touch of hairy caterpillars, but also due to exposure of caterpillar hair blown around by wind (Backe et al. 2021) or buried in soil, frequently making the identification of the cause of such reactions truly difficult, as described by Hesler et al. (1999).

Although we only found three studies reporting on tree related termites in very different urban locations (Brazil, USA, Italy), these appear to be an increasing problem for both urban trees and other structures, including in countries where they were hitherto not an issue. Chouvenc and Foley (2018), for instance, reported this pest as a threat, especially to mature urban trees of historical importance in parts of Florida, US. In the Italian city of Florence, termites were not only damaging trees (roots and wood), but also the wood of nearby historic buildings (Di Domenico and Maistrello 2014). A study by Laverne and Kellogg (2019), on the other hand, found that sound attributes changed due to ash mortality (30%) caused by the emerald ash borer beetle in the Arlington Heights, a suburb of Chicago, US. Human-produced mechanical sounds (anthrophony) were observed to increase, whereas sounds associated with weather (geophony) decreased. Changes in sounds associated with animals (biophony) varied seasonally.

Of studies reporting the *economic impacts* of urban tree insects / pathogens, most focus on the costs of pest management. A majority of these studies were undertaken in US cities and emphasise the costs for municipalities. Such costs can be very significant. In the case of Dutch elm disease, some property owners had to cover the cost for as many as eight tree removals (Bukowski 2019). For larger trees and/or trees in areas requiring more careful removal, tree removal costs can skyrocket (Bukowski 2019). In the case of privately owned trees, city officials rely on private property owners to report. In many cases, private owners will have to cover the costs of tree removal which may make them reluctant to report and / or deal with their diseased tree(s) (Bukowski 2019). In the 1960s, the US city of Syracus not only lacked the manpower to remove an ever increasing number of public and private diseased elm trees, but could no longer afford their removal as there were too many (Bukowski 2019). In the US city of Milwaukee, a major emerald ash borer outbreak was found to have a negative impact on home values for properties located in close proximity to ash trees between 2008 and 2015. The value premium attributed to ash trees throughout the northern 10 zip codes in Milwaukee dramatically diminished after the emerald ash borer outbreak (Li et al. 2019). The establishment of the aforementioned psyllid *M. gladiate* in Moroccan cities, seriously effecting Indian laurel figs, on the other hand, might also compromise nursery production of these plants and increase production costs (Afechtal et al. 2021). Introduction of the red palm mite to north-eastern Brazil, which is the major regional producer of coconuts, is likely to significantly impact the coconut industry in the region, including in urban areas (Oliveira et al. (2016).

Discussion

Ecological, social, and economic impacts of tree insect / pathogens in urban areas around the globe

Managing the impacts of tree insect / pathogen infestation presents major challenges in urban areas worldwide. Our findings reveal the geographic scope and volume of the literature over time, as well as the ways in which the literature reports on various impacts. The growing body of research, characterised by diverse study designs and outcome measures, reports on a wide range of ecological / environmental, social / cultural, and economic impacts of tree insects / pathogens in urban areas in different parts of the world. The increase in publications on this topic with time may indicate a growing interest in urban tree insects / pathogens, but may also be an artefact of a rise in electronic search ability with time which makes it easier to access more recent articles. Although, the wide range of impacts identified in the 28 countries are hard to summarise in a coherent or meaningful way, the range of studies and types of impact identified, and the patterns of insect / pathogen occurrence observed, still allow a synthesis of this information that can help improve urban green infrastructure planning and future tree management strategies. This systematic review provides a good baseline of the range of ecological / environmental, social / cultural, and economic impacts of tree insects / pathogens and potential threats. Considering the different tree canopy cover and role urban trees play across geographic regions, however, the magnitude of these impacts may be considerably different from place to place.

We found many articles reporting serious environmental impacts of tree mortality due to tree insects / pathogens. Dutch elm disease and ash dieback, for instance, have led to substantial elm and ash tree loss in both rural and urban environments of the US, Europe, and more recently also in Russia (e.g., Straw et al. 2013; Lanier et al. 1988). Similarly, the emerald ash borer and the Asian long-horned beetle have caused widespread tree mortality in cities and rural forests (e.g., Haack et al. 1997; Volkovitsh et al. 2021). Ash dieback and emerald ash borer are specialist and only affect ash trees (Fraxinus spp.), the consequences of generalist, multi-host insects or pathogens may pose greater risk to urban and rural landscapes. A recent risk analysis by Sjöman and Östberg (2019), looking at the vulnerability of ten major Nordic cities to potential tree losses caused by the two multi-host Asian longhorned and citrus longhorned beetles estimated that, in the worst-case scenario, 98% of the cities' trees would perish. Non-lethal, though value detracting effects, such as defoliation, decolourisation, deformity, or sooty mouldy leaves are more obvious in the urban forest / trees, compared to rural forests. In cases of substantial and repeated occurrences of these effects, affected tree species may potentially no longer be planted in cities.

Nonetheless, and although the majority of studies reported local aesthetic implications, such as the potential magnitude of visual impacts due to defoliation, and especially tree mortality, there was limited consideration of these as coherent landscape elements, including effects on tree lines, parks, and historic sites. Whereas rural forests are particularly well known for their climate mitigation capacity in form of carbon sequestration (e.g., Favero et al. 2020; Huang et al. 2020), urban trees become increasingly important for climate adaptation, especially to help moderate rising incidences of heatwaves (Loughner et al. 2012; Werbin et al. 2020). Still, we found few studies that linked the impacts of tree insects / pathogens to urban trees' climate adaptation capacity, one of the most prominent ecosystem services. This may be at risk due to tree mortality caused by tree insects / pathogens. In contrast to studies on the economic impacts of tree insects / pathogens on rural forests (e.g., Aukema et al. 2011; Hill et al. 2019) which largely investigate the loss of timber value, those reporting the economic impacts of urban tree insects / pathogens, most focus on the costs of pest management (e.g., Perry and McCain 1988; Sweeney et al. 2020; Sydnor et al. 2011). These studies, however, were all from the US and Canada which limits their generalisability. Still, these costs are likely to accrue in cities around the world and are rising through time. Few studies considered or examined costs for private tree owners, and for litigation costs or damages to structures.

Limitations of study

There are some potential biases and limitations in this review that inform our suggestions for future research in this field. The synthesis was limited to peer-reviewed scientific studies published in English and omitted grey literature; thus, we may not have captured all current and historic research, especially reports and practitioner literature, and this limits the generalisability of the findings. While our selected studies were conducted in cities around the world, they were largely focused in more industrialised, temperate climate regions, with a majority located in Europe and North America. Future reviews, especially on a country or regional level, that also include non-peer reviewed studies and those in other languages could expand our understanding of impacts and generate further, more localised insights about risks. This would be particularly useful for studies conducted on a focused regional range with a similar climate and tree stock, for example on only Europe, Asia, or Africa. A particular challenge was to maintain the focus on urban areas, as much work exists on rural forests, but where impacts may, at times, be similar. Twenty-one originally identified studies did not clearly distinguish between urban and rural environments which led to their exclusion from this synthesis.

Implications of the results for policy, practice, and future research

Policy implications

Growing international trade and climate change are likely to increase the risks posed by tree insects / pathogens with serious implications for the long-term safeguarding and resilience of the urban forest (Potter and Urquhart 2017; Tubby and Webber 2010). In the United States, for instance, urban trees have been estimated to be declining at a rate of roughly four million trees per year due to largely non-native tree insect / pathogen infestations and rapid urbanisation (Nowak and Greenfield 2018) and similar rates have been reported for several other countries (Wolf et al. 2020). In those places most affected, this can have serious impacts in terms of costs, human safety and wellbeing, and to ecosystem services provided, such as local temperature moderation. On the global scale, there have therefore been increasing calls to make international trade safer in terms of biosecurity and to increase efforts to mitigate climate change (e.g.Pyšek et al. 2020; Tubby and Webber 2010). Our review further suggests, that on a more regional and local scale, an increasing armory of tools is being deployed by those who manage and safeguard trees to help identify where pest outbreaks (may) occur and how rapidly they are spreading. The use of risk maps and surveillance alongside density maps and tree inventories can help to develop local control strategies and are additionally useful for communication (Rossi et al. 2016). Of similarly benefit may be lists of insect / pathogen species likely to have more substantial (above background levels) impacts on trees (Aukema et al. 2010).

In some cases, however, there is also evidence that tree species potentially under threat from lethal insect pest / pathogen infestations may be removed or no longer be planted and replaced with a smaller range of 'safe' species. Such biological simplification produces a tree stock which may be even more vulnerable to changing urban environments (Sanders 1981), especially in the context of climatic changes. Urban tree inventories around the globe reveal that although the average abundance of the most common tree species is about 20%, this rises to over 40% in some cities (Lohr et al. 2016). Hence, strategies need to be developed to reach tree managers, including of privately owned trees, largely in household gardens, as well as the wider urban community, to support their understanding of the importance of tree species diversification, the risks of tree insects / pathogens, and how to prevent their unintended spread (Bukowski 2019). On a local scale, a diverse tree population at genus, species and genetic levels may prevent or slow the spread of insects / pathogens and, in the event that they should become established, the overall net impact may be less severe (Zainudin et al. 2012). Above all, adequate funding for both general tree management and pest management are also key to urban tree health and thus delivering the range of services that they provide (McKenney et al. 2012). Considering that urban forestry budgets tend to be limited relative to other urban government priorities, prioritising and providing stable budgets would be an important first step forward. In the case of tree caterpillars affecting human health, Hesler et al. (1999) strongly recommend educating both pest-management and medical personnel and even including information on these in medical intelligence reports.

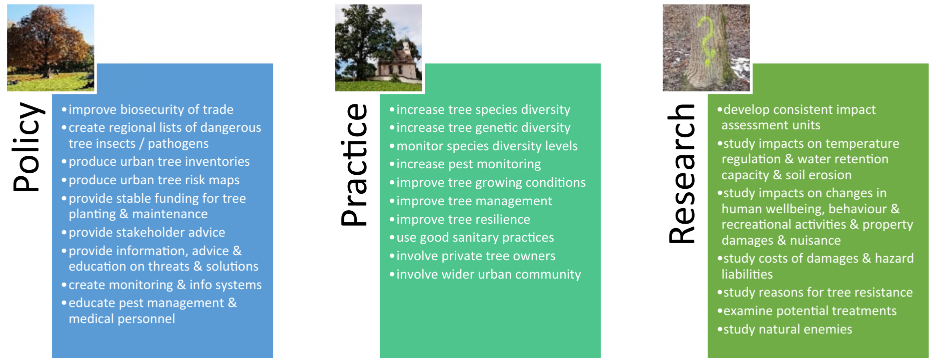
Practical implications

The review suggests that an integrated approach to tree management and safeguarding, combining a range of approaches in a way adapted to location and the range of insect / pathogen species likely to cause problems, is needed to prevent, mitigate or manage the impacts of urban tree insects / pathogens (e.g., Kovač et al. 2021; Chouvenc and Foley 2018). To increase the overall resilience of the urban forest, Raupp et al. (2006) recommends avoiding planting susceptible taxa of trees, especially in those cities/areas that are already overstocked in these taxa and consider diversifying greatly the types of trees. Species diversity levels should be monitored, especially of urban street trees, and planting strategies selected that maintain or enhance these levels (Sanders 1981). Diversification alone, however, cannot solve the growing threat of urban tree insects / pathogens (Bukowski 2019). Past research, for instance on Dutch elm disease, has called attention to the importance of tree and pest management (Bukowski 2019). Achieving a more resilient urban forest canopy also depends upon the will to improve growing conditions for city trees (Bukowski 2019). This may include shared rooting zones, engineered solutions, such as suspended pavements (Greene and Millward 2016), or improving water availability for trees. Sanitary management practices, such as cleaning equipment, boots and leaves under infested trees are also vital (Kopačka et al. 2021). Pavan et al. (2003), for instance, found that removal of fallen leaves of *Aesculus hippocastanum* infested with *Cameraria ohridella* effectively reduced population density and leaf injury during the following year. Early detection through targeted pest monitoring, including of tree nurseries and suppliers was suggested as another crucial component of any pest management programme (e.g., Persad and Tobin 2015; Vakula et al. 2021). This should include reporting insect pests / pathogens, coordinating responses of phytosanitary and other control measures and the creation of a common database (e.g., Orlova-Bienkowskaja 2013). In certain cases, surveys to monitor the presence of natural enemies of insects, and greater support for these, might be useful to help develop pest control strategies (Laudani et al. 2020) and to strengthen natural resilience (Duan et al. 2015).

Further research

This review shed light on some obvious gaps in urban tree insect / pathogen impact research. For instance, detailed studies on the impacts of urban tree insects / pathogens on the important cooling and water retention benefits of urban trees appear to be sparse. This type of information is particularly important in the context of climate change as urban trees / forests can play a key role in climate proofing our cities (Werbin et al. 2020). Studies on the influencing factors which make some specimens resistant to tree insect pests / pathogens (Materska et al. 2022) as well as on effective urban plant protection treatments will be important for future pest management too. Similar to agriculture and gardening, we may also greatly benefit from studying the compatibility and complementarity of different tree species (and in combination with other plants) to develop planting advice with the intention to increase tree resilience. There is also

Fig. 6 Summary of suggestions for policy, practice and research



an urgent need to assess insects / pathogens relative to other threats to urban trees, such as climatic change and increasing urbanisation.

Future research aimed at gaining insights on impacts of urban tree pest / pathogen outbreaks will also benefit from distinguishing more clearly between direct and indirect effects. For instance, we might see direct behavioural changes related to pest management, such as public green managers or homeowners spending more time outdoors to undertake tree inspections or remedial measures (Jones 2016). Similarly, indirect changes may occur in recreational behaviour, for instance, due to loss of environmental aesthetics or risks of allergic reactions. However, no studies were identified covering these types of behavioural changes which may be long-term or even permanent, in some cases. Tracking the change of property value due to insect / pathogen infestations during all stages, including infestation, treatment, removal, and restoration would be useful to guide long-term management plans (Li et al. 2019). Studies could also examine costs of damages and / or hazards, for example from fallen branches or trees or hazard liability, as these are likely to be considerable. There is also a gap in consistent reporting. The use of consistent assessment units to capture the impacts of tree insects / pathogens would help to gain a better understanding. Figure 6 summarises the suggestions for policy, practice and research.

Conclusions

Climate change and growing international trade are likely to increase the threats posed by insects / pathogens to urban trees. A greater understanding of these is therefore vital for effective urban green infrastructure governance and forward planning. We review an abundance of reported ecological / environmental impacts, especially on various tree damages and, tree mortality. The socio-cultural impacts reported focused on aesthetics, health, and hazards, and economic impacts on costs of pest management and control. There are still considerable knowledge gaps in evidence, which may hamper adequate responses to protect the urban forest. Thus, although this review article presents the current available evidence of urban tree insect / pathogen impacts and provides a useful baseline to guide recommendations for policy, management and research, more work using consistent metrics (over time and space) is needed to better forecast how growing threats of insect pest / pathogens will affect the urban forest and to plan for these eventualities.

Supplementary Information The online version contains supplementary data available at https://doi.org/10.1007/s11252-022-01317-5.

Acknowledgements This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement NO. 101023713 for the first author. The article reflects only the authors' view, and the Agency is not responsible for the information it contains. We also thank TUM's and IC's Librarians Birgid Schlindwein and Katharine Thompson for their generous advice on conducting systematic reviews. We also thank Sara Alexandra Salgado and the anonymous reviewers for their valuable comments and suggestions on earlier drafts of the manuscript.

Author contributions Funding acquisition: S. Raum, M. Egerer, S. Pauleit

Conceptualisation: S. Raum, C.M. Collins, J. Urquhart, M. Egerer, S. Pauleit, C. Potter

Methodology: S. Raum, J. Urquhart, C.M. Collins

Analysis: S. Raum, C.M. Collins

Project Administration: S. Raum

Supervision: M. Egerer, S. Pauleit

Visualization: S. Raum, M. Egerer, C.M. Collins

Writing – original draft: S. Raum

Writing – review & editing: S. Raum, M. Egerer, S. Pauleit, C.M. Collins, J. Urquhart, C. Potter

Funding Open Access funding enabled and organized by Projekt DEAL. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement NO. 101023713 for the first author. The article reflects only the authors' view, and the Agency is not responsible for the information it contains.

Data Availability The data that support the findings of this study is freely available on mediaTUM at https://doi.org/10.14459/2022mp1653264.

Declarations

Ethics approval N / A

Consent to participate N / A

Consent for publication N / A

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. The funders had no role in the design of the review; in the collection, analyses, or interpretation of review materials; in the writing of the manuscript, or in the decision to publish the results.

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