REVIEW ARTICLE

The Current State of Resilience Research in Urban Forestry: A Qualitative Literature Review

Sina Rogozinski[1], Somidh Saha[1]*

DOI: 10.18811/ijpen.v7i01.2

Abstract

In the times of enlarging cities and more people living in cities, it is essential to maintain the quality of life for everyone. Urban forests make a significant contribution to this. In urban areas, productive ecosystems are essential to maintain human health and well-being. However, problems like increasing urbanization, changing climate, and pollution in the air, water, and soil can endanger urban ecosystems like urban forests. Having or building resilient urban forests is seen as a possibility to maintain ecosystem services provided by urban forests. Under future conditions, they may become essential for human life in urban areas as some are critical for human health.

This study is a literature review of past research dealing with resilience in urban forests. Forty-one articles published in the years 2006 to 2019 that complied with the search criteria were reviewed. Results show that only three articles used a definition of the resilience of urban trees after disturbance based on a formula; two articles used a definition of resilience based on natural ecosystems. The remaining articles did not define resilience while using the term in the articles.

Out of the reviewed articles, four major themes were identified: urban forest management, urban biodiversity, urban soil, and socio-economic conditions. Nine articles included content about urban soils, 19 articles about urban forest management, 30 articles about urban biodiversity, and 11 articles about socio-economic conditions. As (built) urban forests in cities differ considerably from natural ecosystems, some authors rated monitoring and management actions as necessary, mainly for new establishments and the integration of new species. Authors expressed contradicting opinions on species richness. While some articles suggested focusing on native or endemic species, others proposed to increase species diversity to enhance urban forest resilience. Tolerances and resistances of tree species are essential for urban areas and may gain importance in the future, increasing extreme weather events leading to more frequent pest and disease outbreaks.

Results indicated a focus on urban soil quality as a basis for plant growth, and tree health is an essential factor in urban forestry. Municipal authorities need to adapt management actions to create and maintain an urban forest to the benefits they intend to achieve for the city considering local conditions like climate, species pool, and specific resistances. At the end of the review, a framework recommends actions for a structured collaboration of municipal authorities, researchers, and citizens to achieve resilient urban forests.

Keywords: Adapted species selection, Biodiversity, Climate change adaptation and mitigation, Ecosystem services, Exotic species, Native species, Plant health, Urban forest management, Urban soil.

International Journal of Plant and Environment (2021); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Introduction

Importance of Urban Forests

The expansion of cities leads to replacements of natural ecosystems (Zang *et al.*, 2011), highlighting the importance of preserving existing and building new urban ecosystems. Urban forests are complex ecosystems substantially impacted by humans (Collins *et al.*, 2000; Dobbs *et al.*, 2011). Urban forests can be defined as the system of all single trees, groups of trees, and woodlands in urban and peri-urban environments. It includes forests, street trees, trees in parks and gardens, and trees in derelict corners (FAO, 2016). They can be a habitat for high biodiversity (Alvey, 2006) and additionally provide benefits to the city and its residents (Duryea *et al.*, 2000) by supplying ecosystem services (Konijnendijk, 1997). The concept of ecosystem functions and services goes back to the 1960s (King, 1966) and since then has experienced increased interest (Groot *et al.*, 2002). Ecosystem services provided by urban forests include the improvement of urban climate (Lafortezza *et al.*, 2009), the provision of shadow and shades (Dwyer and Nowak, 2000), the reduction of building energy (Dwyer and Nowak, 2000), and air pollution control (Bottalico *et al.*, 2016). Therefore, urban forests are essential for maintaining or enhancing human health and well-being in urban environments (Nowak and Walton, 2005). Bolund and Hunhammar (1999) identify these cultural ecosystem services as critical relevant ecosystem services in cities. However, urban forests may also render disservices like the release of volatile organic compounds (VOCs) forming ground-level ozone (Lyytimäki and Sipilä, 2009) as well as pollen allergy (Sousa-Silva *et al.* 2021) In addition, the establishment and management of urban forests may cause considerable costs. Overall, the positive effects of ecosystem services dominate over economic costs for urban forests

[1]Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

***Corresponding author:** Somidh Saha, Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, +49 721 608-24644, Email: somidh.saha@kit.edu

How to cite this article: Rogozinski, S., Saha, S. (2021). The Current State of Resilience Research in Urban Forestry: A Qualitative Literature Review. International Journal of Plant and Environment. 7(1), 11-26.

Conflict of interest: None

Submitted: 27/12/2020 **Accepted:** 01/03/2021 **Published:** 15/04/2021

(Dobbs *et al.*, 2011). The benefits of urban forests vary by city as the importance of specific ecosystem services differs depending on local conditions (Wagner and Gobster, 2007).

Urban forests enhance the quality of urban environments due to the ecosystem services (McPherson *et al.*, 2005; Nowak and Walton, 2005; Tyrväinen *et al.*, 2005). The need for ecosystem services is increasing due to global environmental change resulting from urbanization (Guo *et al.*, 2010). Therefore, the value of urban forests is likely to grow with increasing urbanization (Alvey, 2006) and population (Seto *et al.*, 2012). It is necessary to maintain or build urban forests as their ecosystem services support urban areas to adapt to or mitigate climate change effects (Gill *et al.*, 2007). Dobbs *et al.* (2011) state the need to considecities' specific environmental and social conditions to identify adequate urban forest management actions. Management strategies need to be adapted to protect urban forests against current and future threats like climate change, pollution, and urbanization to maintain all advantages for urban areas.

Threats to Urban Forests

Climate change-induced disturbances such as drought, heatwaves, storms, floods (Tratalos *et al.*, 2007), and pollution (Harris and Manning, 2010) impact urban forests in their structure and composition. The rise of sea level will likely lead to saltwater flooding of urban roadways (Hanson *et al.*, 2010), and impact street trees. In addition to climate change, urbanization is putting urban forests at risk as impervious soils caused by paved grounds reduce the life span of trees (Foster and Blaine, 1977; Gilbertson and Bradshaw, 1990). Although at the moment, there is no evidence that urbanization influences large-scale warming (Parker, 2004) resulting from the urban heat island effect, temperatures within cities increase and are problematic for ecosystems as well as the health and well-being of humans in urban areas (Solecki *et al.*, 2005). As a result of climate change and urbanization, droughts represent a major threat in urban areas causing mortality, especially of young trees (Bradshaw *et al.*, 1995; Cameron and Emmett, 2003). Therefore, urban forests must adapt to future climate change (Davoudi *et al.*, 2013). In order to maintain or enhance ecosystem services from urban forests, cities need to develop a guiding strategy (Ernstson *et al.*, 2010). The selection of species with tolerances for specific urban conditions, like the ability to deal with water deficits in highly urbanized areas, is vital for maintaining ecosystem services (Sjöman *et al.*, 2012). In addition, the preservation of urban forests mitigates the problem of air pollution (Kiss *et al.*, 2015; Astiaso Garcia, 2017). Consequently, it is crucial to increase urban forest resilience to preserve its value (Alvey, 2006; Thompson *et al.*, 2009).

Resilience of Urban Forests

Resilience is a component of complex adaptive system dynamics and how to cope with change. It deals with the interaction of gradual and abrupt changes and the capacity of someone or something to adapt to dynamic change (Folke, 2016). It is usually described as the ability to return to its ground state after a disturbance (Schulze and Mooney, 1994). Holling (1973) was one of the first to describe resilience concerning natural ecosystems. His definition is well-known and still commonly used in ecology. He stated that "resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist".

Peterson *et al.* (1998) state that biological diversity seems to be important for the resilience of natural ecosystems. According to Luck *et al.* (2003), diversity of species and populations plays a meaningful role in maintaining ecosystem services as species loss due to disturbance can impact ecosystem functioning and thereby ecosystem services (Elmqvist *et al.*, 2003). Urban ecosystems differ from natural ecosystems (Yan *et al.*, 2019). Urban ecosystems are unique in their climate, soils, and vegetation, and they have unique social dynamics and energy flows (Trepl, 1995; Pickett *et al.*, 1997; Alberti, 2008). For instance, in urban areas, temperatures are higher, and hydrology is different due to increased imperviousness and paved grounds (Alberti, 2005).

Vale and Campanella (2005) define urban resilience as the ability of a city to rebound from a disturbance. Urban resilience refers to the integration of ecological (Alberti and Marzluff, 2004) and social processes at different levels, given the importance of surrounding ecosystems and ecosystem services for humans (Adger, 2000; Brown, 2014). Alberti and Marzluff (2004) assume that the individual behavior of socio-economic systems and ecological systems can differ from the behavior of integrated systems. In addition, they state that the interactions between these complex systems in terms of the resilience of urban ecosystems need to be balanced. In a social-ecological system, resilience is determined by the ability to mitigate change (Berkes *et al.*, 2008) whereby the system responds to changing conditions and disturbances within the desired state (Walker *et al.*, 2004). Urban forests are an example of complex social-ecological systems (Steenberg *et al.*, 2019). Ecosystem services are essential in social-ecological systems and linked to a specific system state. As they are vulnerable to get lost in a different stable state (Folke *et al.*, 2004), it is necessary to avoid changes in the current state. Therefore, it must be understood how to enhance the resilience of urban forests so that they can tolerate disturbances and changes without considering the possibility of transitions to an alternative stable state (Alberti and Marzluff, 2004).

Knowledge Gap and Aim of the Review

The scientific community's views on the resilience of urban forests are currently differing. Depending on the aims of the studies in urban forestry, researchers frequently utilize an existing definition of resilience referring to natural forests. There is a lack of clarity on how resilience can be assessed in urban forests. The use of direct and indirect assessments of resilience complicates the understanding of resilience for urban forests. Due to the lack of established indicators to assess the resilience of urban trees and forests, various factors influencing resilience at a different level are used. While research in ecological resilience is increasing, a basis for terminology is required, to which all researchers can refer and relate their findings. Resilience research mainly concentrates on natural ecosystems and natural forests, whereas only a little research focuses on ecosystems built in urban areas. It is important to increase existing urban forests' resilience and build new urban forests with high resilience. Urban forests need to maintain their ecosystem functions and ecosystem services under future changing conditions. These include increasing urbanization as well as changing climatic conditions like more extreme weather events. Urban planners require scientifically proven knowledge to create resilient urban forests. Hence, it warrants us to review the understanding of resilience in urban forests to global change impacts such as climate change, pollution and urbanization. By reviewing existing literature, t to explore the current state of resilience research in urban forests, including the use and misuse of the terminology of resilience and criteria influencing urban forest resilience. The study's outcome will identify areas requiring additional research and summarize major recommendations for future research.

Material and Methods

This study has been carried out as a qualitative literature review. The literature research followed the steps below.

Literature Search Process and Criteria

A manual search with keywords was performed in publications available online until 31.10.2019 in the ISI Web of Science (1) and CAB Direct (2). Keywords for the search were initially 'climate change', 'drought', 'flooding', 'forest', 'forestry', 'heat', 'pavement', 'paving', 'pipe', 'resilience', 'soil pollution', 'urban', 'urbanization', 'water pollution' and 'pollution' in English. The keywords 'urban forest' or 'urban forestry' were used in combination with one of the above-listed keywords. As the goal was to find articles dealing with resilience in urban forests under either climate change, pollution, or urbanization effects, only articles containing the keywords 'urban forest' or 'urban forestry' and 'resilience' were considered for the review. Articles that did not have the word combination 'urban forest' or 'urban forestry' were omitted. In the ISI Web of Science, 52 articles containing 'urban forest' and 'resilience' were found in the abstract or the articles' keywords. In CAB Direct, the search resulted in 45 articles with considerable overlap with articles from the ISI Web of Science. Articles containing the keywords 'urban forest' or 'urban forestry' and 'resilience' but not discussing resilience of urban forests were eliminated. The 41 articles selected for the review contain at least one time the keywords 'urban forest' or 'urban forestry' and 'resilience.' For a clear distinction between the reviewed articles and the further cited articles, the reviewed articles have been assigned an additional naming convention from LIT1 to LIT41 in alphabetical order.

Data Extraction

The content of each article was structured using a table. The column headings used in this table are listed in Table 1.

Data Analysis

The review of the articles was conducted as a qualitative assessment of the 41 articles. Firstly, the year of publication and the location of each study was evaluated. Subsequently, it was analyzed how the authors define and use the term resilience. Finally, the content of the articles was reviewed to identify similar aspects influencing resilience. This resulted in the four major themes of studies. Those themes were as follows: 1) urban forest management, 2) urban biodiversity, 3) urban soil, and 4) socio-economic conditions (see Table 2). The themes were further divided into subthemes covering recommended actions and action indicators. Recommended actions were a set of management activities recommended by the authors of the articles to increase the overall resilience of urban green space. Action indicators were a specific set of indicators targeted for reforming or improving current management, which can be used to implement and evaluate the recommended actions. These indicators were extracted from the articles.

Results

Frequency and Location of Articles

The majority (76 %) of the articles reviewed was published between 2015 to 2018 (Fig. 1).

Out of the 41 articles reviewed, 36 were based on research studies with most contributions from North America (see Fig. 2 for a global distribution). The remaining five articles were reviews or short communications without explicit geographical reference.

Interpretation of the term Resilience by the Studies

The definition of a resilient urban forest varied widely amongst the reviewed studies. Figure 3 shows the distribution of the definition of resilience used by the authors in the articles.

Three articles measured single tree-based resilience by using a resilience index (D'Amato *et al.*, 2011; D'Amato *et al.*, 2013):

Table 1: Table showing the table structure used as a basis for data extraction of the reviewed articles. Data from each article was entered into the table as available. The detailed table is set out in the appendix.

Authors	*Title*	*Year*	*Location*	*Definition of resilience*
[Authors of the reviewed article]	[Title of the article]	[Year of publication]	Location where the study took place]	Definition of resilience used as a reference in the article and to which author it refers]

Resilience quantified using formula	*Context of resilience use*	*Summary of results*	*Summary of discussion*
[Formula of resilience, when resilience was measured by index]	Context to which resilience referred to when article did not define resilience]	[Summary of the main contents of the results section of the article relevant for this review]	[Summary of the main contents of the discussion section of the article relevant for this review]

Table 2: Categorizing the themes and subthemes of the resilience of urban forests identified in the reviewed articles.

Themes	*Subthemes*
Urban forest management	Planning and monitoring Buildings
Urban biodiversity	Plant species diversity Native and non-native species Tolerances and resistances
Urban soil	Water access Compaction Construction
Socio-economic conditions	social and economic aspects only mentioned as side aspects in reviewed articles

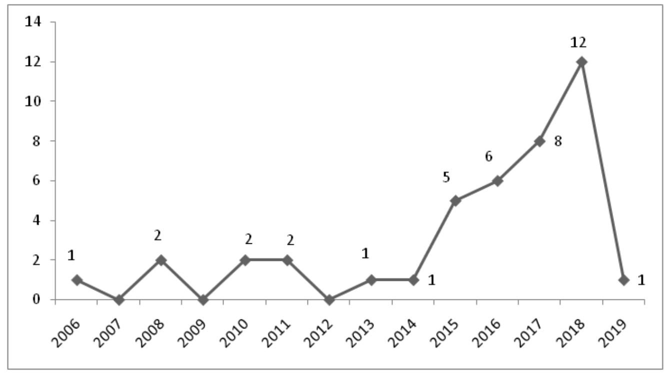

Fig. 1: Graph showing the uneven distribution of the year of publication of the reviewed articles of resilience research in urban forestry. The numbers represent the total number of articles reviewed per year of publication.

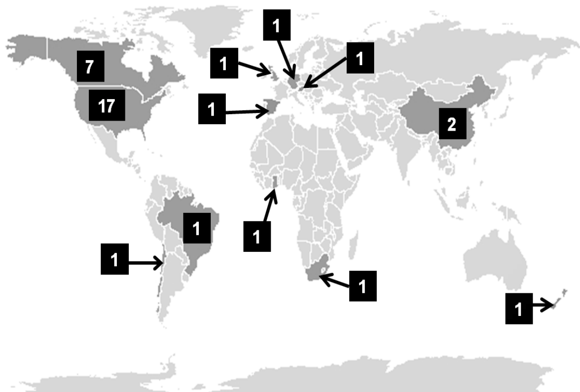

Fig. 2: Map showing the countries of studies of the reviewed articles of resilience research in urban forestry and the numbers represent the total number of studies per country.

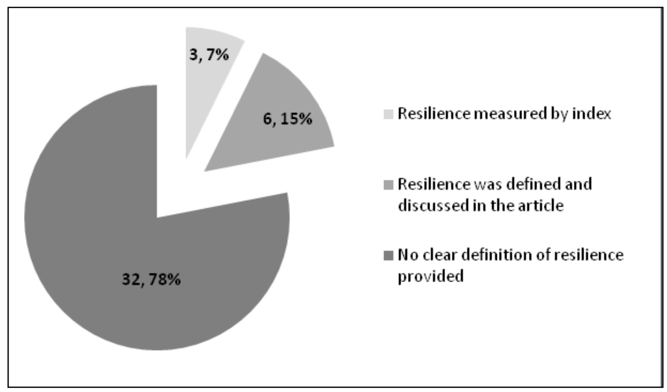

Fig. 3: Chart showing the different use of the term resilience in urban forestry research in the reviewed articles. The numbers and percentages refer to the articles using a definition of resilience measured by the index, the articles defining and discussing resilience, and the articles using the term resilience without providing a clear definition.

$$\text{Resilience Index} = \frac{\text{meanBAI}_{\text{5yr post-disturbance}}}{\text{meanBAI}_{\text{5yr pre-disturbance}}}$$

BAI stands for Basal Area Increment, representing the annual growth of stem thickness in trees (Rubino and McCarthy, 2000). With this index, resilience was defined as the ability of a tree to return its growth to a pre-disturbance level in the period following the disturbance. Two of these articles referred to drought (Fahey *et al.*, 2013, LIT13; Bialecki *et al.*, 2018, LIT3), and one article referred to construction (North *et al.*, 2017, LIT30) as stressors that reduced the growth.

Six other articles defined resilience without an index by either referring to existing definitions or developing their own definitions. Cariñanos *et al.* (2016, LIT5) referred to resilience as the power to mitigate the impacts of future incidents (Maciver and Wheaton, 2005). Carreiro and Zipperer (2011, LIT6) used the definition of resilience as the ability of the reorganization and power of a system to return to its previous state or shift to a different regime (Abel *et al.*, 2006; Walker *et al.*, 2006). Steenberg *et al.* (2017, LIT37) referred to resilience as the ability of a system to withstand stress or to shift back to a previous state after stress (Turner *et al.*, 2003). Pavao-Zuckerman (2008, LIT32) was the only author who linked the definition of resilience to C.S. Holling's early theory (1973). He included the additional aspect of urban areas and applied Suding *et al.* (2004) definition describing resilience as the ability of a system to change from degraded to a more favorable state. Without referring to an existing definition, Hale *et al.* (2015, LIT15) defined resilience as showing "continuity in the desirable aspects of system performance, despite disturbance or restructuring of the system itself." Morgenroth *et al.* (2016, LIT28) described resilience as the time required by an urban forest to "return to normal function after disturbance."

All other articles used the term resilience without providing any definition. However, several authors discussed resilience in various contexts. For instance, Chen *et al.* (2017, LIT7), Karlo and Sajna (2017, LIT20), and McPherson *et al.* (2018, LIT25) contextualized resilience with stability. At the same time, Costanza *et al.* (2015, LIT9) and Brandt *et al.* (2016, LIT4) related resilience to the vulnerability of ecosystems. On the one hand, Millward *et al.* (2011, LIT27), Jim *et al.* (2018, LIT19), Steenberg (2018, LIT36), and Ziter *et al.* (2019, LIT41) prioritized resilience of cities in general over the resilience of urban forests. On the other hand, McClung and Ibáñez (2018, LIT24) related resilience of urban forests to tree and plant health.

Major Themes of the Articles

The reviewed articles were classified into the four major themes urban forest management, urban biodiversity, urban soil, and socio-economic conditions (Fig. 4). Most of the reviewed articles fitted in more than one theme as they provided statements on and recommendations for several themes.

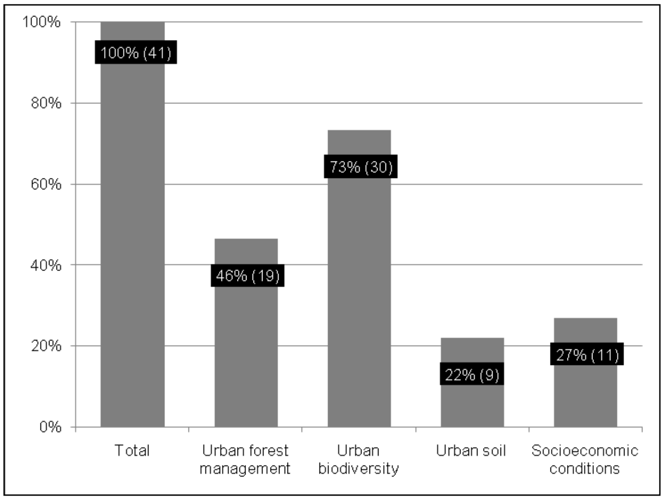

Fig. 4: Chart showing the frequency of the four major themes urban forest management, urban biodiversity, urban soil, and socio-economic conditions discussed in the reviewed articles. The percentages and numbers represent the proportions and absolute numbers of the reviewed articles discussing each major theme.

Urban Forest Management

In total, 19 articles related resilience to urban forest management. Sixteen articles discussed management planning and monitoring of urban forests to increase climate change, whereas 7 articles emphasized building density and urban forest management on resilience. There were overlaps between the theme of planning, monitoring to building density in some articles.

Planning and Monitoring

Keeping the vulnerability of the urban system low (Steenberg *et al.*, 2017, LIT37) by adapting the urban forest to future climate conditions (van Doorn and McPherson, 2018, LIT39) as well as by creating diversity in species, species composition, and ages (Steenberg *et al.*, 2017, LIT37; McPherson *et al.*, 2018, LIT25; van Doorn and McPherson, 2018, LIT39) can increase the resilience of the urban forest ecosystems (Steenberg *et al.*, 2017, LIT37). In addition, maintaining ecosystem services provided by urban forests was important for cities' resilience (Ziter *et al.*, 2019, LIT41). see actions and related indicators for the subtheme planning and monitoring based on the recommendations of the reviewed articles is listed in Table 3.

Building Density

Costanza *et al.* (2015, LIT9) viewed urbanization as a bigger problem than climate change in the survival of urban forests. Therefore, the role of urbanization needed to be considered when planning or managing urban forests. Jim *et al.* (2018, LIT19) recommended precise planning for dense urban areas for ensuring resilient urban forests. Table 4 lists the actions and

Table 3: An overview of the reviewed articles' recommended actions and action indicators for the subtheme planning and monitoring within the major theme urban forest management. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Sufficient knowledge base (2)	• Good education and training	LIT10; LIT12
Inclusive stakeholder collaboration (2)	• Good governance through stakeholder participation inclusion of planners, local citizens, municipal tree officers, urban foresters	LIT19; LIT28
Long-term planning (3)	• Developing long-term urban forest management strategies • Creation of urban forest management plans	LIT1; LIT10; LIT19
Consideration of infrastructure and resources (5)	• The scale of the city and surrounding conditions of the planting site (location, open space, building density) • Increase in governmental funding for urban forest conservation, management, and planning	LIT1; LIT10; LIT15 LIT21; LIT39
Correct species selection (5)	• The right composition of the urban forest species • Developing selection criteria (native/non-native, resistances/tolerances, adaptations to changing climates) • Creating diversity in species, species composition and ages	LIT1; LIT25; LIT37; LIT39; LIT41
Proper soil maintenance (3)	• Good soil quality with enough root volume • Reduction of compacted soils • Reduction of traffic on vulnerable soils	LIT26; LIT27 LIT29
Adequate irrigation (2)	• Irrigation of young plants irrigation during dry periods	LIT10; LIT26
Passive restoration after disturbance (1)	• Limited human interventions after disturbance in a particular type of urban forests such as extensive urban woodlands to allow natural succession and increase diversity	LIT 6

Table 4: Recommended actions and action indicators of the reviewed articles for the subtheme building density. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Adapting species selection (5)	• Right species to find for each location, depending on the type of buildings and infrastructure around • Planting of species that can be suitable for the adaptation to limited resource supply, water stress under impervious or paved ground	LIT11, LIT15, LIT19, LIT24,LIT36
Increased planting area (2)	• Inclusion of private properties for tree planting (to minimize risks of damage through underground infrastructure)	LIT15; LIT41

related indicators for the subtheme building density based on the recommendations of the reviewed articles.

Summary of the Theme Urban Forest Management and its Implication on Resilience

Urban forest management was identified as one of the key elements of urban forest resilience addressed in the reviewed literature. Whereas urban forest planning and monitoring were well-researched, the sub-theme building density lacked strategies for solving the problems identified with highly urbanized areas. The majority of authors agreed on the need for adequate planning and monitoring of urban forests to preserve or achieve resilience. This required appropriate governance and long-term planning by improving and reforming urban forest management plans. The strategies discussed for monitoring urban forests included keeping constantly good soil quality, irrigation for healthy plant and tree conditions, and maintaining the desirable species composition. Consequently, each city needs to adapt the planning to consider the local conditions like infrastructure, climate, and budget.

In contrast to most articles' planning and monitoring strategies, Carreiro and Zipperer (2011, LIT6) suggested relying on the self-recovery of the disturbed area. As this was only valid under specific conditions, it cannot be seen as a general recommendation.

Most of the articles emphasized the importance of urbanization in urban forest management in terms of building density. Urbanization was identified as a problem, however, the effects of urbanization on urban forests were seldomly studied. Appropriate species selection and an increased planting area were the main strategies for keeping the resilience of urban forests concerning building density. Only Dahlhausen *et al.* (2018, LIT11) claimed to prefer plantings of older trees in built-up areas due to their adaptation to special conditions.

Although considerable research on planning methods for building urban forests was done, two additional areas require further research. First, adequate planning strategies and species compositions adapted to densely built-up areas are currently missing. In addition, there is a lack of management and monitoring strategies for trees in areas surrounded by above and below ground constructions.

Urban Biodiversity

Thirty articles had discussed the theme of urban biodiversity. There overlapping themes can be identified, which were a) plant and tree species diversity (14 articles), b) native and non-native species (18 articles), and c) tolerances and resistances to stressors (8 articles).

Plant and Tree Species Diversity

According to Barron *et al.* (2016, LIT2), Brandt *et al.* (2016, LIT4), Morgenroth *et al.* (2016, LIT28), Karlo and Sajna (2017, LIT20), diversity was directly associated with the resilience of urban forest. In urban areas, the impact of stress and disturbance on plant species composition was lower than in the natural environment (Guo *et al.*, 2018, LIT14). The list of recommended actions and indicators for the sub-theme plant and tree species diversity is presented below (Table 5).

Native and Non-native Species

Urban forests often had many non-native species (Chen *et al.*, 2017, LIT7; Hernández and Villaseñor, 2018, LIT17). Species richness and abundance of non-native was higher in urban centers than in peri-urban areas (Nero and Anning, 2018, LIT29). This could have been due to the spreading of non-native species from gardens in residential urban areas (Zhao *et al.*, 2010, LIT40; Mavimbela *et al.*, 2018, LIT23). Diverse communities were less vulnerable to non-native species invasion, implying that the non-native species' ability to grow and spread (i.e. invasiveness) was more concerning than the number of non-native species (Mandryk and Wein, 2006, LIT22). The recommended actions and their indicators are presented in Table 6.

Tolerances and Resistances

Tolerances and resistances of urban tree species and their relevance in urban biodiversity were widely discussed in the literature. The recommended actions and indicators are listed in Table 7.

Summary of the Theme Urban Biodiversity and Resilience

The majority of authors agreed on diversity being linked to a resilient urban forest. Thereby, articles differentiated between species richness, diversity in genus or family, or diversity in age. While some articles mentioned focusing on diversity is more important than a native or endemic urban forest for achieving resilience; others tended to prefer either native or non-native species. Only one article claimed increased canopy cover is more important than diversity, native status, and pest considerations (Conway and Vander Vecht, 2015, LIT8). Several articles recommended focusing on planting species with resistances and tolerances, mainly referring to drought, pests, and diseases, and specific conditions in urban areas like paved ground. As future climate models forecast weather extremes like droughts and heat waves (McPherson *et al.*, 2018, LIT25), research in this respect is required. The studies showed a general lack of research on biological diversity as the focus was on urban flora, whereas the role of fauna influencing urban forest resilience was poorly researched.

Table 5: An overview of recommended actions and action indicators of the reviewed articles for the subtheme plant and tree species diversity. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Consider overall diversity (4)	• Diversity to be maximized at the level of age, species, genera or family, • Contextualization of urban forests with 10/20/30 rule regarding species classification (species, genus, family) by Santamour (1990)	LIT2, LIT15, LIT20, LIT21
Consider factors controlling species diversity (1)	• Tree density and tree imperviousness	LIT36
Increasing tree species richness (5)	• Resilient urban forest consists of many species, species richness or diversity in tree species important for maintaining and maximizing ecosystem services, • Increase species and genus diversity of street trees, • Change management strategies for replacements of damaged or dead tree (e.g. not planting the same species as earlier)	LIT2; LIT5; LIT10, LIT20, LIT39
Increase soil faunistic diversity (1)	• Use metrics of ant biodiversity to observe ecosystem conditions and services	LIT33
Monitoring impact of climate change on pollen emission (1)	• Changing climates affect pollen emission, complicates preservation of diversity due to different effects on species	LIT5
Monitoring of mycorrhiza (4)	• Growth of mycorrhiza to be monitored	LIT38
Increasing biomass (2)	• Distribution and amount of biomass	LIT28, LIT8
Suitable species selection for planting (2)	• For new planting or replacements consider criteria like site aspect, available space, appearance of the mature tree, proximity to buildings, and the intended use	LIT39; LIT8

Table 6: An overview of recommended actions and action indicators of the reviewed articles for the subtheme native and non-native species. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Preference for native species (5)	• Preferring native and endemic species for urban forests (preserve native and endemic species) urban forest management plan favors native species increase genetic diversity spread urban remnants into surrounding gardens for conservation of native urban woody species	LIT8; LIT31; LIT1, LIT25, LIT12
Preference for non-natives (4)	• Non-native species necessary to build or remain resilient urban forest as native species might be at the limit of their range adaptation to future climates required need for species with tolerances and resistances (e.g. cultivars) • Preference of non-natives due to site restrictions and poor site conditions dependent on variety of regional tree flora (regions with only few woody species more likely to use non-native species since better adaptations to urbanized conditions like paved areas) pest and disease resistant cultivars and non-native species to increase diversity (challenge: little information on species' behavior, risk of invasiveness)	LIT4; LIT8; LIT1, LIT35
Need to control spread of non-natives (7)	• Fast-growing non-native species can establish on open, disturbed or unmanaged habitats increasing costs from invasiveness due to need of intensive • Long-term management lowest risks of displacing native species with assisted migration – failure of assisted migration results in loss of time and money non-native species planted due to exotic appearance with increased risk of becoming invasive	LIT32; LIT6 LIT31; LIT14; LIT25 LIT1; LIT7
Combination of natives and non-natives (4)	• Finding the right combination of increasing native and allowing non-native species is best species with resistances to pests and diseases depending on location	LIT2; LIT21; LIT35

Urban Soil

Nine articles discussed the associations between urban soil and the resilience of urban forests. Five articles discuss the access of urban soil water, and four articles reported compaction of urban soils—only 1 article reported on the influence of urban construction on urban soil and its implication on resilience.

Water Access

Fahey *et al.* (2013, LIT13) found urban plantings often having low competition in the ground and a high water-holding capacity. They concluded a potential resistance and resilience of trees to droughts. Two studies directly measured drought resilience. The results did not negatively impact resilience despite differences in severity and duration of the droughts (Fahey *et al.*, 2013,

Table 7: An overview of recommended actions and action indicators of the reviewed articles for the subtheme tolerances and resistances. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Species selection with target-oriented adaptations (8)	• Increased amount of species tolerant to cold, drought, and heat • Plantings of species tolerant to flooding and increased salinity in coastal areas • Species tolerant to salt in irrigated urban areas • Species resistant to pests and diseases • Identification of species with resistances to poor or impervious soils and pollution	LIT4; LIT14; LIT16; LIT24; LIT25; LIT26; LIT31; LIT35

Table 8: An overview of recommended actions and action indicators of the reviewed articles for the subtheme water access. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Guarantee sufficient availability of water and resources (1)	• Soil water level needs to be monitored in urban forest areas (e.g. network of soil moisture sensors)	LIT24
Adapted species selection (3)	• Species tolerant to drought as response to increasing water stress identification of species for specific climate conditions with predicted leaf water potential at turgor loss (PSI)	LIT39; LIT3 LIT34
Planting of larger trees (1)	• Older trees with bigger size should be selected for planting to reduce mortality due to drought	LIT39
Enlarging the treeplanting area (1)	• Higher resource availability due to higher growing space above and below ground	LIT39

LIT13; Bialecki *et al.*, 2018, LIT3). Only droughts lasting longer than one growing season could lead to more negative effects up to tree mortality (Fahey *et al.*, 2013, LIT13). The actions and related indicators for the subtheme water access based on the recommendations of the reviewed articles is listed above (Table 8).

Compaction

The problem of soil compaction on the quality of urban soil has been discussed in 4 studies listed below (Table 9).

Construction

Only one article (LIT30) recommended increasing the above and below ground growing space during an urban tree planting at the time of house and infrastructure construction and related it to the resilience of urban trees. It reported higher survival of trees in dense urban areas after construction which were given to more above and below ground growing space.

Summary of the Theme Urban Soil and Resilience

There was an agreement among authors that good soil quality and water availability were essential for urban forest growth and therefore were linked to the resilience of urban forests. Literature on the effects of compaction and construction on tree growth and survival in the context of resilience was rare. The majority of articles found water availability in the soil essential for tree growth in urban areas and provided different recommendations for increasing the resilience of urban forests. These recommendations were usually given by only one article and cannot be generalized.

The authors agreed that compacted soil negatively impacted tree growth, especially in combination with drought (McClung and Ibáñez, 2018, LIT24). Therefore, species with adaptations to impervious surfaces were recommended for affected areas. In addition, the authors recommended improving the quality of the planting area. North *et al.* (2017, LIT30) stated that street trees were neither resistant nor resilient to construction as root damage led to trees investing in building new roots rather than increasing the stem taper. As only one study dealt with the effects of construction, there is no scientific base for further application. More research in the three subthemes of urban soil is needed to create meaningful recommendations for enhancing the resilience of urban forests. Additionally, further research is required to find recommendations for planting methods and species adapted to disturbance from construction.

Socio-economic Conditions

Out of the four major themes influencing urban forest resilience, socio-economic conditions were discussed the least. Eleven articles commented on social or economic conditions influencing the resilience of urban forests, but none emphasized this theme. Furthermore, there were no subthemes identified due to the limited number of statements and only three recommended actions.

Doody *et al.* (2010, LIT12) and Carreiro and Zipperer (2011, LIT6) reported the social-ecological system as important for ecological resilience. They suggested considering social and cultural aspects for establishing urban forests and achieving a working urban system. In addition, Steenberg *et al.* (2017, LIT37) stated vulnerability being a part of social-ecological systems and resilience being used for "researching urban social-ecological systems." Resilience concepts could be integrated into a "conceptual framework of vulnerability" (Steenberg *et al.*, 2017, LIT37). The vulnerability of ecosystems to the effects of climate change was influenced by biological and social aspects, including cultivars or management adaption (Brandt *et al.*, 2016, LIT4).

Table 10 lists the actions and related indicators for the subtheme planning and monitoring based on the recommendations of the reviewed articles. Social or economic aspects influencing the resilience of urban forests were only side aspects in the reviewed articles. Most of the articles agreed that social aspects influence the resilience of urban forests or at least urban forest management planning. Only the influence

Table 9: An overview of recommended actions and action indicators of the reviewed articles for the subtheme compaction. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Adapted species selection (2)	• Non-native species potentially better adapted to increased imperviousness preference of older trees being better adapted to increased imperviousness	LIT34 LIT11
Enlarging the tree planting area (1)	• Increased growing space enhances tree health by reducing soil compaction	LIT2
Improving soil quality (1)	• Increasing understorey vegetation cover and diversity can lead to higher root density in the topsoil and contribute in higher soil quality by enhancing soil organic matter	LIT27

Table 10: An overview of recommended actions and action indicators of the reviewed articles for the theme socio-economic conditions. The number in brackets shows the total number of articles recommending the action.

Recommended actions	*Action indicators*	*Articles*
Monitored tree species composition (2)	• Partly driven by housing attributes and biophysical conditions foraging species (non stable and can change over time)	LIT36; LIT18
Increased quality of greening space (1)	• Policy change to ensure higher quality of greening space versus higher quantity	LIT7
Adapted planning to social needs (4)	• Consideration of neighborhood needs influence of socio-economic status on tree species richness and abundance (native and exotic species) preference for older trees to minimize effects of vandalism	LIT14; LIT17; LIT19; LIT31

of residents' status on the selection and richness of species was emphasized by the articles. Social, cultural, and economic aspects influencing urban forest resilience do not get enough attention in urban forestry and require further research.

Discussion

A qualitative review of 41 articles dealing with resilience in urban forests was conducted to assess the current state of the art in resilience research in urban forestry and identify shortcomings and future needs for further research. In the reviewed articles, increasing resilience was seen as one of the main goals in urban forestry, even though a precise definition of resilience for urban forests was lacking. The authors claimed the importance of urban forests and their preservation due to their provision of ecosystem services. The content of the articles has been clustered into the four major themes urban forest management, urban biodiversity, urban soil, and socio-economic conditions. The themes except for socio-economic conditions have been further divided into subthemes. Within each subtheme and the theme socio-economic conditions, recommended actions and action indicators for the resilience of urban forests have been identified. In the following discussion, the recommended actions will be analyzed regarding their importance for future resilience research.

Understanding of Resilience in the Studies

Research on urban forest resilience is in the early stages. As multiple environmental factors impact urban forests, the reviewed studies discussed resilience inconsistently. The reviewed articles focused on different environmental conditions. The environmental conditions, like the local climate in the study regions, differed as they covered eleven different countries on five continents. Conway and Vander Vecht (2015, LIT8), for example, focused on urban forests in Canada, and Carreiro and Zipperer (2011, LIT6) researched urban forests in Brazil. The number of studies per environmental condition was limited. The studies are differentiated in structure, methodology, and aims. For example, Fahey *et al.* (2013, LIT13) focused on measuring tree growth of different species to determine whether trees were resilient to drought. Sjöman *et al.* (2015, LIT34) analyzed existing literature regarding drought tolerance of a specific genus.

The authors discussed the four major themes for urban forest resilience with different emphases. Due to the lack of a generally accepted definition of resilience, authors applied a definition of resilience adapted to their study aims. Some authors did not clarify whether they used ecological, social, or economic resilience as their reference. It was found that most authors did not define resilience. Articles referred to existing definitions of resilience from other authors, similar to Holling's (1973) definition but without directly referring to Holling. These definitions of resilience were based on natural ecosystems like forests. Only Pavao-Zuckerman (2008, LIT32) stated a possible difference in the resilience definition of natural versus built urban areas. Authors defining resilience by index instead referred to Holling's (1973) definition of stability than to the definition of resilience as they focused on returning to a previous state after a disturbance. One of the studies assumed that measuring resilience by tree growth after construction was not a reliable proof of resilience as trees focused on rebuilding roots instead of stem growth (North *et al.*, 2017, LIT30). Other authors linked the term resilience to various contexts without providing any definition of resilience.

Recommended Actions and Action Indicators

The differences in structure, methodology, and aims of the reviewed articles led to various recommended actions. Despite the identified inconsistency in understanding resilience, the review results showed comparable recommended actions that seemed to be strongly interdependent. The results indicated that adapted species selection was a critical factor for resilience in three out of the four themes (urban forest management, urban biodiversity, urban soil). Future research should focus on adapted species selection while considering the interaction with other recommended actions. Therefore, the environmental conditions, climate, soil, and water need to be considered. As climate change impacts cities, urban forests need to adapt to changing climates. Cities are already planting trees with tolerances to drought climate, which will be beneficial in further warming. Since trees in the outer areas of forests are more negatively affected by warming than the inner forest (McClung and Ibáñez, 2018, LIT24), selected species with tolerances to drought and heat should be planted edge. Resilience to drought depends on species and is influenced by forest stand composition (Jourdan *et al.*, 2020). Trees can be resilient to drought as root metabolism can recover after a drought. The impact of drought varies depending on the intensity and length of the drought and the tree age stages (Hagedorn *et al.*, 2016). This is confirmed by the findings of Fahey *et al.* (2013, LIT13) and Bialecki *et al.* (2018, LIT3), where drought effects on grown trees were examined.

In addition to climate conditions, adapted species selection must consider surrounding soil conditions, including the intensity of urbanization at the planting area. Studies showed that soil properties might be used to project the growth of street trees (Scharenbroch and Catania, 2012). However, details on soil properties that positively affect tree growth in urban areas are hardly researched (Ghosh *et al.*, 2016). On roadsides, parking lots, or construction sites, water, and oxygen absorption is limited through soil compaction (Sillick and Jacobi, 2009). Soil compaction is one of the significant factors stressing tree growth and is difficult to undo once it emerged on a planting site (Coder, 2007). Millward *et al.* (2011, LIT27) researched the impacts of parkland naturalization. Through root expansion and biological activity, soil compaction can be reduced, which leads to higher water infiltration rates. These results cannot be generalized due to missing comparable studies and should be further researched as a possible solution for urban forests like parks. As trees at roadsides are often planted into gaps of paved surfaces, species with a tolerance for compacted soil conditions and drought are required (Blunt, 2008). Construction is a common disturbance affecting urban forests due to the renovation of old buildings and construction of new ones and has not been studied sufficiently (Steenberg *et al.*, 2017, LIT37). Construction activities can injure trees through soil compaction and root damage leading to tree decline and mortality (Hauer *et al.*, 1994; Trowbridge and Bassuk, 2004). So far, too little research is done for conclusions about the impact of paving, infrastructure, and other urbanization effects on the resilience of urban forests (Mullaney *et al.*, 2015).

Adaptations of tree species to unique environmental conditions in urban areas like changing infrastructure and resource availability due to urbanization and climate change are essential. This requires a species selection based on resistances and tolerances. Resistances of trees to pests will become more important in urban forests as an increasing variety of hosts due to the introduction of non-native species increases the range of pests (Garrett *et al.*, 2006). Warming and resulting drought conditions may increase the abundance of pests in urban forests as trees suffering from water stress are more likely to get attacked by pests (Dale and Frank, 2014). These projections are consistent with the findings on the saplings from Meineke and Frank (2018, LIT26). Different tree species may react differently to water stress and pest attack. Depending on the city's location, effects may be different, as the impact might be less problematic in tropical areas than in temperate forests (Gely *et al.*, 2020). On the contrary, urbanization may negatively impact herbivores (Schueller *et al.*, 2019) and reduce damages in urban forests (Moreira *et al.*, 2019).

Research needs to identify species with resistances and tolerances to local conditions considering the importance of species diversity. The reviewed articles show a divided opinion on the use of native or non-native species. In addition to the reviewed articles, other authors suggest maintaining a high amount of native species (e.g., Yan *et al.*, 2019). Alvey (2006) proposes to prefer native species, but non-natives and cultivars adapted to urban conditions should be planted when required. Assisted migration to introduce new species to the current species pool must be balanced with potential adverse effects like increased costs (Pedlar *et al.*, 2012). Messier *et al.* (2019) suggest finding species with complementary functional traits to increase resilience. These non-native species need to be non-invasive to limit the required monitoring and management of urban forests in the future. Jactel *et al.* (2017) and Bauhus *et al.* (2017) state that in natural forests, increased diversity leads to more resistance to stress, disturbances, and changing conditions. Research should identify if this were applicable to urban forests. Mori *et al.* (2013) suggest redirecting the focus on species diversity in current research towards response diversity allowing urban forests to adapt to uncertain environmental changes while keeping the ecosystem functions. A controversial opinion is presented by Millward *et al.* (2011, LIT27), allowing disturbed areas to recover without human interference under specific conditions to increase soil quality and bring original plant species diversity back. However, depending on the area, this approach may lead to fast-growing non-native species dominating slower growing native species (van Kleunen *et al.*, 2010).

High diversity is associated with positive effects on ecosystem services (Balvanera *et al.*, 2006). Thompson *et al.* (2009) assume that a loss of diversity affects ecosystem services and goods provided by natural forests. Brandt *et al.* (2016, LIT4) conclude that diversity plays a similarly important role in resilience research regarding forests in urban environments. Street trees consisting of few species have a higher susceptibility to pests and diseases (Alvey, 2006), resulting in reduced ecosystem services (Livesley *et al.*, 2016). Several findings in the reviewed articles refer to the importance of diversity for ecosystem functions of natural forests. Future research needs to validate their application to urban forests. Invasion of non-native species leading to a loss of diversity can impact ecosystem functions of forests (Hopper *et al.*, 2005). Forests with low species richness provide fewer goods and services than complex forest ecosystems (Thompson *et al.*, 2009). Changing environmental conditions can affect biodiversity, impacting ecosystems in long-term (Smith *et al.*, 2009). Species with no specific purpose in the past become essential for ecosystem resilience under environmental changes (Thompson *et al.*, 2009). Hooper *et al.*

(2005) assume that functional diversity and species composition are of higher importance for ecosystem functions than diversity per se due to redundancy. Species richness in forests is relevant as redundancy is essential under changing environmental conditions frequently occurring in urban areas. Overall, species diversity needs to be balanced against ecosystem services provided by urban forests.

As ecosystem services are essential for cities, municipal officers should work closely with urban forest researchers to integrate their findings into urban forest planning strategies. Their research results on adapted species selection should be the basis of urban forest management and monitoring. Urban forest management plans are required to increase and improve urban greenings and forests. They help assess problems coming up while building or restoring resilient urban forests as species selection depends on the type of urban forest with different environmental conditions. For example, street trees planted at roadsides require a different adaptation than species planted for urban parks. Strategies for planning, managing, and monitoring urban forests differ between articles, although long-term strategies were mentioned as a basis for achieving healthy and resilient urban forests. D'Amato *et al.* (2011) stated mitigation of or adaptation to climate change effects as long-term strategies regarding forest management. This review shows that both strategies are used in urban forest management as urban forests provide ecosystem services like pollution mitigation and develop tolerances and resistances to adapt to changing environmental conditions. The management of urban forests is linked to high costs (van Doorn and McPherson, 2018, LIT39) (e.g., for forest establishment, maintenance, replacement, watering, cuttings), which are likely to increase in the future (Miller *et al.*, 2015). Cities are challenged with the handling of the budget for (intensive) urban forest management.

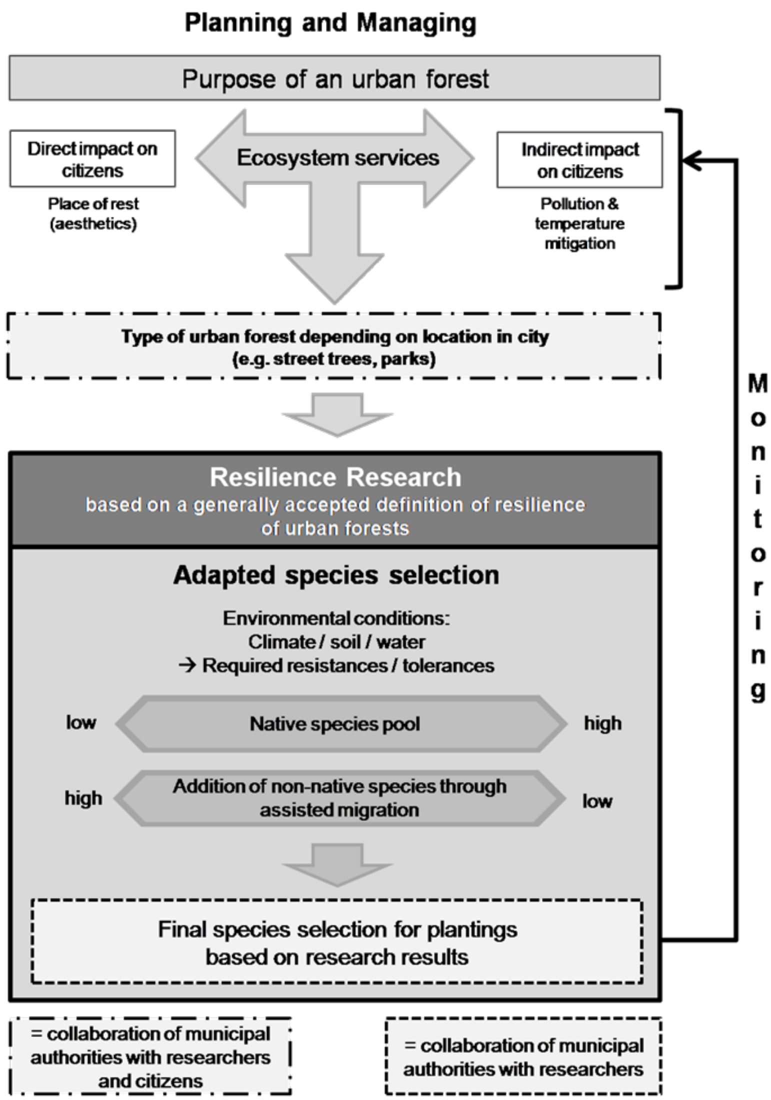

Fig. 5: Framework illustrating the interdependency of recommended actions for achieving a resilient urban forest focusing on adapted species selection. The different borders indicate the collaboration of the stakeholders (municipal authorities, researchers, citizens). The desired ecosystem services required for the city determine the type of urban forest. Resilience research identifies the required species pool adapted to environmental conditions. Continuous monitoring of the final plantings ensures a resilient urban forest and the delivery of ecosystem services.

A structured communication between decision-makers and citizens is critically important (Morgenroth *et al.*, 2016, LIT28), confirmed by other authors (Kenney *et al.*, 2011). The diverging objectives of citizens need to be considered to avoid conflicts (Escobedo *et al.,* 2011) as the socio-economic status of urban areas affects biodiversity. Fewer biodiversity is found in areas with low socio-economic status, whereas in areas with a higher status (Hernández and Villaseñor, 2018, LIT17), urban forests are influenced by residents through their choice of garden species (Kinzig *et al.*, 2005). Most important ecosystem services need to be identified to sustain human health and well-being when focusing on conservation and management (Mori *et al.*, 2013). Especially in dense urban areas, greenings are a possible solution to mitigate air pollution and heat island impacts being a major problem for cities (Nowak *et al.*, 2006). Escobedo *et al.* (2011) recommend balancing the goal of pollution reduction against goals with a higher benefit for the city and potentially requiring another type of urban forest structure. When planning to integrate private land into the urban forest, landowners focus on aesthetics and low maintenance of species, while urban planners aim to achieve the essential ecosystem services for the city (Ziter *et al.,* 2019, LIT41). Private landowners with gardens need to be trained on species supporting human health and well-being in the city (Conway, 2016).

The recommended actions identified in the reviewed articles cover a broad span of measures that have been studied individually without considering their mutual dependency. The framework (Fig. 5) takes this interdependency into account with a structured combination of recommended actions to achieve a resilient urban forest. The basis for this framework is a generally accepted definition of resilience that needs to be developed. As the recommended actions impact different stakeholder groups, the framework also indicates the required collaboration between municipal authorities, researchers, and citizens. The planning of an urban forest needs to be based on the purpose municipal officers want to achieve. Urban areas depend on specific ecosystem services provided by urban forests. Therefore, all management actions for urban forests need to focus on building and maintaining these ecosystem services. They might include pollution mitigation via individual street trees or a cooling effect of the complete urban forest for the whole city. In addition, urban parks offer citizens the possibility of a place of rest and recreation. When the required type of urban forest is determined, resilience research needs to identify the species pool adapted to environmental conditions. The best combination of native and non-native species needs to be found. The final species selection for the plantings based on the research results is done in collaboration with municipal officers. Ongoing monitoring is required to ensure that the urban forest is resilient and delivers the desired ecosystem services. With further research regarding the resilience of urban forests, the framework might be adapted and improved.

Limitations

The review focused on peer-reviewed articles in the English language. There could, therefore, be the possibility of linguistic bias. Definitions of the resilience of forests refer to natural forests. Only a few urban forests are based on a natural forest relict; most urban forests are anthropogenic built ecosystems. It is, therefore, questionable if the definition of resilience can be applied to urban forests. This may be a reason why authors are not defining resilience for urban forests. The articles reviewed lack of comparability due to diverse study aims and study structures and do not allow drawing general conclusions regarding the resilience of urban forests.

Outlook

Several authors of the reviewed articles propose that urban forestry requires further research. Based on the review results, future research should focus on adapted species selection considering environmental conditions. Especially, the effects of construction, paved surfaces, and building density on the resilience of urban forests are insufficiently researched. Studies of resilience research in urban forestry are mainly conducted in North America. All other continents require further investigation as previous studies took place under widely differing climate conditions impeding the provision of generally valid statements. Little consideration in resilience research was put on adaptation strategies to (increased) pollution of water, air, and soil. Only the mitigation of air pollution by trees is an aspect of urban forestry research. However, the impact of pollution on urban forests has not been considered so far. Future studies in urban forestry should focus on determining indicators for measuring resilience. Applying similar study structures would increase the comparability of outcomes. Future research could focus on soil microbiota and mycorrhiza (van Geel *et al.*, 2019) and the relation between flora and fauna. As urban forests comprise a high number of animal species contributing to seed disposal or pollination, a decline in number would indicate a decreasing resilience (Thompson *et al.*, 2009). The socio-ecological and socio-economic aspects of resilience are hardly considered in the reviewed articles. An increased planting and use of foraging species might combine ecological, social, and economic factors. Cities could plant trees offering usable products for residents. Urban food forestry is of growing interest in cities and has already been studied in future changing climate conditions (Clark and Nicholas, 2013). This approach could be integrated into the resilience research of urban forests. Further research is needed regarding the effects of greening projects described by Chen *et al.* (2017, LIT7) as the pure increase of greenings without considering species adaptation might negatively impact the environment long-term.

Conclusion

A standard definition of resilience in the context of urban forestry was missing. Therefore, researchers either used definitions referring to natural ecosystems or no definition at all. This resulted in differing opinions on when urban forests were seen as resilient and which factors influenced their resilience. Climate change was the most frequently mentioned environmental aspect influencing urban forests, as many articles discussed drought or water stress, followed by urbanization. Pollution was only mentioned in terms of pollution reduction as part of ecosystem services provided by urban forests rather than the influence of pollution on urban forests. The majority of authors agreed that adapted species selection was a critical factor for increasing urban forest resilience. However, authors had opposed opinions on the diversity of species being more favorable for increasing resilience than a specific amount of native or exotic species.

Furthermore, environmental conditions needed to be considered to identify required resistances and tolerances. Especially the quality of urban soils, including water holding capacity, was essential for tree growth in urban areas, with soils often being compacted or in another way degraded. Results indicated that planning and managing future urban forests should be based on the local climate, the type of urban forest, and its purpose regarding ecosystem services. Monitoring urban forests and urban drought situations (e.g., soil moisture and storage capacity) is required to maintain the ecosystem functions, and services. Researchers and municipal authorities should collaborate to ensure an appropriate species selection, and citizens should be included in discussions to create a shared understanding of the purpose of urban forests.

Future research should focus on the suitability of species adapted to environmental conditions in urban areas. Especially, increasing the resilience of urban forests in dense areas, under construction, on degraded soils, and under increasing pollution need to be studied.

References

Searched databases

CAB International. (Wallingford, Oxfordshire, United Kingdom). cabdirect.org (Accessed: 02.07.2020).

Clarivate Analytics. (Boston, Massachusetts, United States of America). webofknowledge.com (Accessed: 02.07.2020).

List of Literature Reviewed in this Study

LIT1: Almas, A.D. and Conway, T.M. (2016) The role of native species in urban forest planning and practice: A case study of Carolinian Canada. *Urban Forestry & Urban Greening*, 17, 54-62. Available at: doi:10.1016/j.ufug.2016.01.015.

LIT2: Barron, S., Sheppard, S. and Condon, P. (2016) Urban Forest Indicators for Planning and Designing Future Forests. *Forests*, 7(12), 208. Available at: doi:10.3390/f7090208.

LIT3: Bialecki, M.B., Fahey, R.T. and Scharenbroch, B. (2018) Variation in urban forest productivity and response to extreme drought across a large metropolitan region. *Urban Ecosystems*, 21(1), 157-169. Available at: doi:10.1007/s11252-017-0692-z.

LIT4: Brandt, L., Derby Lewis, A., Fahey, R., Scott, L., Darling, L. and Swanston, C. (2016) A framework for adapting urban forests to climate change. *Environmental Science & Policy*, 66, 393-402. Available at: doi:10.1016/j.envsci.2016.06.005.

LIT5: Cariñanos, P., Casares-Porcel, M., La Guardia, A.V.D. de, La Cruz-Márquez, R.D. and La Guardia, C.D. de (2016) Charting trends in the evolution of the La Alhambra forest (Granada, Spain) through analysis of pollen-emission dynamics over time. *Climatic Change*, 135(3-4), 453-466. Available at: doi:10.1007/s10584-015-1589-6.

LIT6: Carreiro, M.M. and Zipperer, W.C. (2011) Co-adapting societal and ecological interactions following large disturbances in urban park woodlands. *Austral Ecology*, 36(8), 904-915. Available at: doi:10.1111/j.1442-9993.2010.02237.x.

LIT7: Chen, W.Y., Hu, F.Z.Y., Li, X. and Hua, J. (2017) Strategic interaction in municipal governments' provision of public green spaces: A dynamic spatial panel data analysis in transitional China. *Cities*, 71, 1-10. Available at: doi:10.1016/j.cities.2017.07.003.

LIT8: Conway, T.M. and Vander Vecht, J. (2015) Growing a diverse urban forest: Species selection decisions by practitioners planting and supplying trees. *Landscape and Urban Planning*, 138, 1-10. Available at: doi:10.1016/j.landurbplan.2015.01.007.

LIT9: Costanza, J.K., Terando, A.J., McKerrow, A.J. and Collazo, J.A. (2015) Modeling climate change, urbanization, and fire effects on Pinus palustris ecosystems of the southeastern U.S. *Journal of Environmental Management*, 151, 186-199. Available at: doi:10.1016/j.jenvman.2014.12.032.

LIT10: Cowett, F.D. and Bassuk, N.L. (2017) Street Tree Diversity in Three Northeastern U.S. States. *Arboriculture & Urban Forestry*, 43(1), 1-14.

LIT11: Dahlhausen, J., Rötzer, T., Biber, P., Uhl, E. and Pretzsch, H. (2018) Urban climate modifies tree growth in Berlin. *International Journal of Biometeorology*, 62(5), 795-808. Available at: doi:10.1007/s00484-017-1481-3.

LIT12: Doody, B.J., Sullivan, J.J., Meurk, C.D., Stewart, G.H. and Perkins, H.C. (2010) Urban realities: the contribution of residential gardens to the conservation of urban forest remnants. *Biodiversity and Conservation*, 19(5), 1385-1400. Available at: doi:10.1007/s10531-009-9768-2.

LIT13: Fahey, R., Carter, D.R. and Bialecki, M.B. (2013) Tree Growth and Resilience to Extreme Drought Across an Urban Land-use Gradient. *Arboriculture & Urban Forestry*, 39(6), 279-285.

LIT14: Guo, P., Su, Y., Wan, W., Liu, W., Zhang, H. and Sun, X. *et al.* (2018) Urban Plant Diversity in Relation to Land Use Types in Built-up Areas of Beijing. *Chinese Geographical Science*, 28(1), 100-110. Available at: doi:10.1007/s11769-018-0934-x.

LIT15: Hale, J., Pugh, T., Sadler, J., Boyko, C., Brown, J. and Caputo, S. *et al.* (2015) Delivering a Multi-Functional and Resilient Urban Forest. *Sustainability*, 7(4), 4600-4624. Available at: doi:10.3390/su7044600.

LIT16: Hallett, R., Johnson, M.L. and Sonti, N.F. (2018) Assessing the tree health impacts of salt water flooding in coastal cities: A case study in New York City. *Landscape and Urban Planning*, 177, 171-177. Available at: doi:10.1016/j.landurbplan.2018.05.004.

LIT17: Hernández, H.J. and Villaseñor, N.R. (2018) Twelve-year change in tree diversity and spatial segregation in the Mediterranean city of Santiago, Chile. *Urban Forestry & Urban Greening*, 29, 10-18. Available at: doi:10.1016/j.ufug.2017.10.017.

LIT18: Hurley, P.T. and Emery, M.R. (2018) Locating provisioning ecosystem services in urban forests: Forageable woody species in New York City, USA. *Landscape and Urban Planning*, 170, 266-275. Available at: doi:10.1016/j.landurbplan.2017.09.025.

LIT19: Jim, C.Y., van den Konijnendijk Bosch, C. and Chen, W.Y. (2018) Acute Challenges and Solutions for Urban Forestry in Compact and Densifying Cities. *Journal of Urban Planning and Development*, 144(3), 4018025. Available at: doi:10.1061/(ASCE)UP.1943-5444.0000466.

LIT20: Karlo, T. and Sajna, N. (2017) Biodiversity related understorey stability of small peri-urban forest after a 100-year recurrent flood. *Landscape and Urban Planning*, 162, 104-114. Available at: doi:10.1016/j.landurbplan.2017.02.012.

LIT21: Kendal, D., Dobbs, C. and Lohr, V.I. (2014) Global patterns of diversity in the urban forest: Is there evidence to support the 10/20/30 rule? *Urban Forestry & Urban Greening*, 13(3), 411-417. Available at: doi:10.1016/j.ufug.2014.04.004.

LIT22: Mandryk, A.M. and Wein, R.W. (2006) Exotic vascular plant invasiveness and forest invasibility in urban boreal forest types. *Biological Invasions*, 8(8), 1651-1662. Available at: doi:10.1007/s10530-005-5874-6.

LIT23: Mavimbela, L.Z., Sieben, E.J.J. and Procheş, Ş. (2018) Invasive alien plant species, fragmentation and scale effects on urban forest community composition in Durban, South Africa. *New Zealand Journal of Forestry Science*, 48(1), 213. Available at: doi:10.1186/s40490-018-0124-8.

LIT24: McClung, T. and Ibáñez, I. (2018) Quantifying the synergistic effects of impervious surface and drought on radial tree growth. *Urban Ecosystems*, 21(1), 147-155. Available at: doi:10.1007/s11252-017-0699-5.

LIT25: McPherson, E.G., Berry, A.M. and van Doorn, N.S. (2018) Performance testing to identify climate-ready trees. *Urban Forestry & Urban Greening*, 29, 28-39. Available at: doi:10.1016/j.ufug.2017.09.003.

LIT26: Meineke, E.K. and Frank, S.D. (2018) Water availability drives urban tree growth responses to herbivory and warming. *Journal of Applied Ecology*, 55(4), 1701-1713. Available at: doi:10.1111/1365-2664.13130.

LIT27: Millward, A.A., Paudel, K. and Briggs, S.E. (2011) Naturalization as a strategy for improving soil physical characteristics in a forested urban park. *Urban Ecosystems*, 14(2), 261-278. Available at: doi:10.1007/s11252-010-0153-4.

LIT28: Morgenroth, J., Östberg, J., van den Konijnendijk Bosch, C., Nielsen, A.B., Hauer, R. and Sjöman, H. *et al.*(2016) Urban tree diversity—Taking stock and looking ahead. *Urban Forestry & Urban Greening*, 15, 1-5. Available at: doi:10.1016/j.ufug.2015.11.003.

LIT29: Nero, B.F. and Anning, A.K. (2018) Variations in soil characteristics among urban green spaces in Kumasi, Ghana. *Environmental Earth Sciences*, 77(8), 151. Available at: doi:10.1007/s12665-018-7441-3.

LIT30: North, E.A., D'Amato, A.W., Russell, M.B. and Johnson, G.R. (2017) The influence of sidewalk replacement on urban street tree growth. *Urban Forestry & Urban Greening*, 24, 116-124. Available at: doi:10.1016/j.ufug.2017.03.029.

LIT31: Ordóñez, C. and Duinker, P.N. (2015) Climate change vulnerability assessment of the urban forest in three Canadian cities. *Climatic Change*, 131(4), 531-543. Available at: doi:10.1007/s10584-015-1394-2.

LIT32: Pavao-Zuckerman, M.A. (2008) The Nature of Urban Soils and Their Role in Ecological Restoration in Cities. *Restoration Ecology*, 16(4), 642-649. Available at: doi:10.1111/j.1526-100X.2008.00486.x.

LIT33: Sanford, M.P., Manley, P.N. and Murphy, D.D. (2009) Effects of urban development on ant communities: implications for ecosystem services and management. *Conservation Biology : the Journal of the Society for Conservation Biology*, 23(1), 131-141. Available at: doi:10.1111/j.1523-1739.2008.01040.x.

LIT34: Sjöman, H., Hirons, A.D. and Bassuk, N.L. (2015) Urban forest resilience through tree selection—Variation in drought tolerance in Acer. *Urban Forestry & Urban Greening*, 14(4), 858-865. Available at: doi:10.1016/j.ufug.2015.08.004.

LIT35: Sjöman, H., Morgenroth, J., Sjöman, J.D., Sæbø, A. and Kowarik, I. (2016) Diversification of the urban forest—Can we afford to exclude exotic tree species? *Urban Forestry & Urban Greening*, 18, 237-241. Available at: doi:10.1016/j.ufug.2016.06.011.

LIT36: Steenberg, J.W.N. (2018) People or place? An exploration of social and ecological drivers of urban forest species composition. *Urban Ecosystems*, 21(5), 887-901. Available at: doi:10.1007/s11252-018-0764-8.

LIT37: Steenberg, J.W.N., Millward, A.A., Nowak, D.J. and Robinson, P.J. (2017) A conceptual framework of urban forest ecosystem vulnerability. *Environmental Reviews*, 25(1), 115-126. Available at: doi:10.1139/er-2016-0022.

LIT38: Tonn, N. and Ibáñez, I. (2017) Plant-mycorrhizal fungi associations along an urbanization gradient: implications for tree seedling survival. *Urban Ecosystems*, 20(4), 823-837. Available at: doi:10.1007/s11252-016-0630-5.

LIT39: van Doorn, N.S. and McPherson, E.G. (2018) Demographic trends in Claremont California's street tree population. *Urban Forestry & Urban Greening*, 29, 200-211. Available at: doi:10.1016/j.ufug.2017.11.018.

LIT40: Zhao, M., Escobedo, F.J. and Staudhammer, C. (2010) Spatial patterns of a subtropical, coastal urban forest: Implications for land tenure, hurricanes, and invasives. *Urban Forestry & Urban Greening*, 9(3), 205-214. Available at: doi:10.1016/j.ufug.2010.01.008.

LIT41: Ziter, C.D., Pedersen, E.J., Kucharik, C.J. and Turner, M.G. (2019) Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the United States of America*, 116(15), 7575-7580. Available at: doi:10.1073/pnas.1817561116.

Literature cited

Abel, N., Cumming, D.H.M. and Anderies, J.M. (2006) Collapse and Reorganization in Social-Ecological Systems: Questions, Some Ideas, and Policy Implications. *Ecology and Society*, 11(1). Available at: doi:10.5751/ES-01593-110117.

Adger, W.N. (2000) Social and ecological resilience: are they related? *Progress in Human Geography*, 24(3), 347-364. Available at: doi:10.1191/030913200701540465.

Alberti, M. (2005) The Effects of Urban Patterns on Ecosystem Function. *International Regional Science Review*, 28(2), 168-192. Available at: doi:10.1177/0160017605275160.

Alberti, M. (2008) *Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems*. Springer Science+Business Media LLC: Boston, MA.

Alberti, M. and Marzluff, J.M. (2004) Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. *Urban Ecosystems*, 7(3), 241-265. Available at: doi:10.1023/B:UECO.0000044038.90173.c6.

Alvey, A.A. (2006) Promoting and preserving biodiversity in the urban forest. *Urban Forestry & Urban Greening*, 5(4), 195-201. Available at: doi:10.1016/j.ufug.2006.09.003.

Astiaso Garcia, D. (2017) Green areas management and bioengineering techniques for improving urban ecological sustainability. *Sustainable Cities and Society*, 30, 108-117. Available at: doi:10.1016/j.scs.2017.01.008.

Balvanera, P., Pfisterer, A.B., Buchmann, N., He, J.-S., Nakashizuka, T. and Raffaelli, D. *et al.* (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecology Letters*, 9(10), 1146-1156. Available at: doi:10.1111/j.1461-0248.2006.00963.x.

Bauhus, J., Forrester, D.I. and Pretzsch, H. (2017) Mixed-Species Forests: The Development of a Forest Management Paradigm, 76, 1-25. Available at: doi:10.1007/978-3-662-54553-9_1.

Berkes, F., Colding, J. and Folke, C.(E.) (2008) *Navigating social-ecological systems: Building resilience for complexity and change*. Cambridge Univ. Press: Cambridge.

Blunt, S.M. (2008) Trees and pavements - are they compatible?*Arboricultural Journal*, 31(2), 73-80. Available at: doi:10.1080/03071375.2008.9747522.

Bolund, P. and Hunhammar, S. (1999) Ecosystem services in urban areas. *Ecological Economics*, 29(2), 293-301. Available at: doi:10.1016/S0921-8009(99)00013-0.

Bottalico, F., Chirici, G., Giannetti, F., Marco, A. de, Nocentini, S. and Paoletti, E. *et al.* (2016) Air Pollution Removal by Green Infrastructures and Urban Forests in the City of Florence. *Agriculture and Agricultural Science Procedia*, 8, 243-251. Available at: doi:10.1016/j.aaspro.2016.02.099.

Bradshaw, A., Hunt, B. and Walmsley, T. (1995) *Trees in the urban landscape: Principles and practice*. E & FN Spon: London.

Brown, K. (2014) Global environmental change I. *Progress in Human Geography*, 38(1), 107-117. Available at: doi:10.1177/0309132513498837.

Cameron, R.W.F. and Emmett, M.R. (2003) Plants in the environment: amenity horticulture.: In: Thomas, B., Murphy, D. and Murray, B. (eds.) The Encyclopedia of Applied Plant Sciences. Elsevier Science Ltd., London, 735 -742.

Clark, K.H. and Nicholas, K.A. (2013) Introducing urban food forestry: a multifunctional approach to increase food security and provide ecosystem services. *Landscape Ecology*, 28(9), 1649-1669. Available at: doi:10.1007/s10980-013-9903-z.

Coder, K.D. (2007) *Soil compaction stress and trees: Symptoms, measures, treatments*.

Collins, J., Fagan, W., Grimm, N., Hope, D., Kinzig, A. and Wu, J. *et al.* (2000) A New Urban Ecology. *American Scientist*, 88(5), 416. Available at: doi:10.1511/2000.5.416.

Conway, T.M. (2016) Tending their urban forest: Residents' motivations for tree planting and removal. *Urban Forestry & Urban Greening*, 17, 23-32. Available at: doi:10.1016/j.ufug.2016.03.008.

Dale, A.G. and Frank, S.D. (2014) Urban warming trumps natural enemy regulation of herbivorous pests. *Ecological Applications : a Publication of the Ecological Society of America*, 24(7), 1596-1607. Available at: doi:10.1890/13-1961.1.

D'Amato, A.W., Bradford, J.B., Fraver, S. and Palik, B.J. (2011) Looking back to inform the future:: The effects of thinning and stand complexity on drought tolerance within Pinus resinosa systems. Paper presented at the Eighth North Aemrican Forest Ecology Workshop: Forest Ecology in a Managed Landscape., Roanoke, VA.

D'Amato, A.W., Bradford, J.B., Fraver, S. and Palik, B.J. (2013) Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. *Ecological Applications : a Publication of the Ecological Society of America*, 23(8), 1735-1742. Available at: doi:10.1890/13-0677.1.

Davoudi, S., Brooks, E. and Mehmood, A. (2013) Evolutionary Resilience and Strategies for Climate Adaptation. *Planning Practice and Research*, 28(3), 307–322. Available at: doi:10.1080/02697459.2013.787695.

Dobbs, C., Escobedo, F.J. and Zipperer, W.C. (2011) A framework for developing urban forest ecosystem services and goods indicators. *Landscape and Urban Planning*, 99(3-4), 196-206. Available at: doi:10.1016/j.landurbplan.2010.11.004.

Duryea, M.L., Kaempf Binelli, E. and Korhnak, V. (2000) Restoring the urban forest ecosystem: SW-140, Restoring the Urban Forest Ecosystem, a CD-ROM Produced by the School of Forest Resources and Conservation, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

Dwyer, J.F. and Nowak, D.J. (2000) A national assessment of the urban forest: an overview. *Society of American Foresters 1999 National Convention Portland, Oregon*, 157-162.

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J. and Walker, B. *et al.* (2003) Response diversity, ecosystem change, and resilience. *Frontiers in Ecology and the Environment*, 1(9), 488-494. Available at: doi:10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2.

Ernstson, H., van der Leeuw, S.E., Redman, C.L., Meffert, D.J., Davis, G. and Alfsen, C. *et al.* (2010) Urban transitions: on urban resilience and human-dominated ecosystems. *Ambio*, 39(8), 531-545. Available at: doi:10.1007/s13280-010-0081-9.

Escobedo, F.J., Kroeger, T. and Wagner, J.E. (2011) Urban forests and pollution mitigation: analyzing ecosystem services and disservices. *Environmental Pollution (Barking, Essex : 1987)*, 159(8-9), 2078-2087. Available at: doi:10.1016/j.envpol.2011.01.010.

FAO (2016) Guidelines on urban and peri-urban forestry Rome: F. Salbitano, S. Borelli, M. Conigliaro, Y. Chen (Eds.), FAO Forestry Paper No. 178, Food and Agriculture Organization of the United Nations,

Folke, C. (2016) Resilience (republished). *Ecology and Society*, 21(4).

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T. and Gunderson, L. *et al*. (2004) Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, 35(1), 557-581. Available at: doi:10.1146/annurev.ecolsys.35.021103.105711.

Foster, R.S. and Blaine, J. (1977) Urban tree survival: trees in the sidewalk. *J. Arboric*, 4(1), 14–17.

Garrett, K.A., Dendy, S.P., Frank, E.E., Rouse, M.N. and Travers, S.E. (2006) Climate change effects on plant disease: genomes to ecosystems. *Annual Review of Phytopathology*, 44, 489-509. Available at: doi:10.1146/annurev.phyto.44.070505.143420.

Gely, C., Laurance, S.G.W. and Stork, N.E. (2020) How do herbivorous insects respond to drought stress in trees? *Biological Reviews of the Cambridge Philosophical Society*, 95(2), 434-448. Available at: doi:10.1111/brv.12571.

Ghosh, S., Scharenbroch, B.C., Burcham, D., Ow, L.F., Shenbagavalli, S. and Mahimairaja, S. (2016) Influence of soil properties on street tree attributes in Singapore. *Urban Ecosystems*, 19(2), 949-967. Available at: doi:10.1007/s11252-016-0530-8.

Gilbertson, P. and Bradshaw, A.D. (1990) THE SURVIVAL OF NEWLY PLANTED TREES IN INNER CITIES. *Arboricultural Journal*, 14(4), 287-309. Available at: doi:10.1080/03071375.1990.9746850.

Gill, S.E., Handley, J.F., Ennos, A.R. and Pauleit, S. (2007) Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environment*, 33(1), 115-133. Available at: doi:10.2148/benv.33.1.115.

Groot, R.S. de, Wilson, M.A. and Boumans, R.M.J. (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Available at: doi:10.1016/S0921-8009(02)00089-7.

Guo, Z., Zhang, L. and Li, Y. (2010) Increased dependence of humans on ecosystem services and biodiversity. *PloS One*, 5(10). Available at: doi:10.1371/journal.pone.0013113.

Hagedorn, F., Joseph, J., Peter, M., Luster, J., Pritsch, K. and Geppert, U. *et al.* (2016) Recovery of trees from drought depends on belowground sink control. *Nature Plants*, 2, 16111. Available at: doi:10.1038/NPLANTS.2016.111.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J. and Herweijer, C. *et al.* (2010) A global ranking of port cities with high exposure to climate extremes. Available at: doi:10.1007/s10584-010-9977-4.

Harris, T.B. and Manning, W.J. (2010) Nitrogen dioxide and ozone levels in urban tree canopies. *Environmental Pollution (Barking, Essex : 1987)*, 158(7), 2384–2386. Available at: doi:10.1016/j.envpol.2010.04.007.

Hauer, R.J., Miller, R.W. and Ouimet, D.M. (1994) Street tree decline and construction damage. *Journal of Arboriculture*, (20), 94.

Holling, C.S. (1973) Resilience and stability of ecological systems. *Annual review of ecology and systematics*, 4(1), 1–23.

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P. and Lavorel, S. *et al.* (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecological Monographs*, 75(1), 3-35. Available at: doi:10.1890/04-0922.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B. and Gardiner, B. *et al.* (2017) Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. *Current Forestry Reports*, 3(3), 223-243. Available at: doi:10.1007/s40725-017-0064-1.

Jourdan, M., Kunstler, G. and Morin, X. (2020) How neighbourhood interactions control the temporal stability and resilience to drought of trees in mountain forests. *Journal of Ecology*, 108(2), 666-677. Available at: doi:10.1111/1365-2745.13294.

Kenney, W.A., van Wassenaer, P. and Satel, A.L. (2011) Criteia and indicators for strategic urban forest planning and management. *Arboriculture & Urban Forestry*, 37(3), 108-117.

King, R.T. (1966) Wildlife and man. *New York Conservationist*, 20(6), 8-11.

Kinzig, A.P., Warren, P., Martin, C., Hope, D. and Katti, M. (2005) The Effects of Human Socioeconomic Status and Cultural Characteristics on Urban Patterns of Biodiversity. *Ecology and Society*, 10(1). Available at: doi:10.5751/ES-01264-100123.

Kiss, M., Takács, Á., Pogácsás, R. and Gulyás, Á. (2015) The role of ecosystem services in climate and air quality in urban areas: Evaluating carbon sequestration and air pollution removal by street and park trees in Szeged (Hungary). *Moravian Geographical Reports*, 23(3), 36-46. Available at: doi:10.1515/mgr-2015-0016.

Konijnendijk, C.C. (1997) A short history of urban forestry in Europe. *J. Arboriculture*, 23(1), 31-39.

Lafortezza, R., Carrus, G., Sanesi, G. and Davies, C. (2009) Benefits and well-being perceived by people visiting green spaces in periods of heat stress. *Urban Forestry & Urban Greening*, 8(2), 97-108. Available at: doi:10.1016/j.ufug.2009.02.003.

Livesley, S.J., McPherson, G.M. and Calfapietra, C. (2016) The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *Journal of Environmental Quality*, 45(1), 119-124. Available at: doi:10.2134/jeq2015.11.0567.

Luck, G.W., Daily, G.C. and Ehrlich, P.R. (2003) Population diversity and ecosystem services. *Trends in ecology & evolution*, 18(7), 331-336. Available at: doi:10.1016/S0169-5347(03)00100-9

Lyytimäki, J. and Sipilä, M. (2009) Hopping on one leg – The challenge of ecosystem disservices for urban green management. *Urban Forestry & Urban Greening*, 8(4), 309–315. Available at: doi:10.1016/j.ufug.2009.09.003.

Maciver, D.C. and Wheaton, E. (2005) Tomorrow's Forests: Adapting to a Changing Climate, 394, 273-282. Available at: doi:10.1007/1-4020-4166-7-13.

McPherson, G., Simpson, J.R., Peper, P.J., Maco, S.E. and Xiao, Q. (2005) Municipal forest benefits and costs in five US cities. *Journal of Forestry*, 103(8), 411–416.

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R. and Nolet, P. *et al.* (2019) The functional complex network approach to foster forest resilience to global changes. *Forest Ecosystems*, 6(1), 617. Available at: doi:10.1186/s40663-019-0166-2.

Miller, R.W., Hauer, R.J. and Werner, L.P. (2015) *Urban forestry: Planning and managing urban greenspaces*, 3rd edn. Waveland Press, Inc: Long Grove (Illinois).

Moreira, X., Abdala-Roberts, L., Berny Mier y Teran, J.C., Covelo, F., La Mata, R. de and Francisco, M. *et al.* (2019) Impacts of urbanization on insect herbivory and plant defences in oak trees. *Oikos*, 128(1), 113-123. Available at: doi:10.1111/oik.05497.

Mori, A.S., Furukawa, T. and Sasaki, T. (2013) Response diversity determines the resilience of ecosystems to environmental change. *Biological Reviews of the Cambridge Philosophical Society*, 88(2), 349–364. Available at: doi:10.1111/brv.12004.

Mullaney, J., Lucke, T. and Trueman, S.J. (2015) A review of benefits and challenges in growing street trees in paved urban environments.

Landscape and Urban Planning, 134, 157–166. Available at: doi:10.1016/j.landurbplan.2014.10.013.

Nowak, D.J. and Walton, J.T. (2005) Projected urban growth (2000-2050) and its estimated impact on the US forest resource. *Journal of Forestry*, 103(8), 383–389. Available at: doi:10.1093/jof/103.8.383.

Nowak, D.J., Crane, D.E. and Stevens, J.C. (2006) Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, 4(3-4), 115–123. Available at: doi:10.1016/j.ufug.2006.01.007.

Parker, D.E. (2004) Climate: large-scale warming is not urban. *Nature*, 432(7015), 290. Available at: doi:10.1038/432290a.

Pedlar, J.H., McKenney, D.W., Aubin, I., Beardmore, T., Beaulieu, J. and Iverson, L. *et al.* (2012) Placing Forestry in the Assisted Migration Debate. *BioScience*, 62(9), 835–842. Available at: doi:10.1525/bio.2012.62.9.10.

Peterson, G., Allen, C.R. and Holling, C.S. (1998) Original Articles: Ecological Resilience, Biodiversity, and Scale. *Ecosystems*, 1(1), 6–18. Available at: doi:10.1007/s100219900002.

Pickett, S.T.A., Burch Jr., W.R., Dalton, S.E., Foresman, T.W., Grove, J.M. and Rowntree, R. (1997) A conceptual framework for the study of human ecosystems in urban areas. *Urban Ecosystems*, 1(4), 185–199. Available at: doi:10.1023/A:1018531712889.

Rubino, D.L. and McCarthy, B.C. (2000) Dendroclimatological Analysis of White Oak (Quercus alba L., Fagaceae) from an Old-Growth Forest of Southeastern Ohio, USA. *Journal of the Torrey Botanical Society*, 127(3), 240. Available at: doi:10.2307/3088761.

Scharenbroch, B.C. and Catania, M. (2012) Soil quality attributes as indicators of urban tree performance. *Arboriculture and Urban Forestry*, 38(5), 214.

Schueller, S.K., Paul, S., Payer, N., Schultze, R. and Vikas, M. (2019) Urbanization decreases the extent and variety of leaf herbivory for native canopy tree species Quercus rubra, Quercus alba, and Acer saccharum. *Urban Ecosystems*, 22(5), 907–916. Available at: doi:10.1007/s11252-019-00866-6.

Schulze, E.-D. and Mooney, H.A. (1994) Ecosystem Function of Biodiversity: A Summary. In: Schulze, E.-D. and Mooney, H.A. (Eds.) *Biodiversity and ecosystem function: With 22 tables*. Springer: Berlin, pp. 497–510.

Seto, K.C., Güneralp, B. and Hutyra, L.R. (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America*, 109(40), 16083–16088. Available at: doi:10.1073/pnas.1211658109.

Sillick, J.M. and Jacobi, W.R. (2009) Healthy roots and healthy trees. *Gardening series. Diseases. (*2926).

Sjöman, H., Östberg, J. and Bühler, O. (2012) Diversity and distribution of the urban tree population in ten major Nordic cities. *Urban Forestry & Urban Greening*, 11(1), 31–39. Available at: doi:10.1016/j.ufug.2011.09.004.

Smith, M.D., Knapp, A.K. and Collins, S.L. (2009) A framework for assessing ecosystem dynamics in response to chronic resource alterations induced by global change. *Ecology*, 90(12), 3279–3289. Available at: doi:10.1890/08-1815.1.

Solecki, W.D., Rosenzweig, C., Parshall, L., Pope, G., Clark, M. and Cox, J. *et al.* (2005) Mitigation of the heat island effect in urban New Jersey. *Environmental Hazards*, 6(1), 39–49. Available at: doi:10.1016/j.hazards.2004.12.002.

Sousa-Silva, R., Smargiassi, A., Kneeshaw, D. *et al.* Strong variations in urban allergenicity riskscapes due to poor knowledge of tree pollen allergenic potential. *Sci Rep* **11,** 10196 (2021). https://doi.org/10.1038/s41598-021-89353-7

Steenberg, J.W.N., Duinker, P.N. and Nitoslawski, S.A. (2019) Ecosystem-based management revisited: Updating the concepts for urban forests. *Landscape and Urban Planning*, 186, 24–35. Available at: doi:10.1016/j.landurbplan.2019.02.006.

Suding, K.N., Gross, K.L. and Houseman, G.R. (2004) Alternative states and positive feedbacks in restoration ecology. *Trends in Ecology & Evolution*, 19(1), 46–53. Available at: doi:10.1016/j.tree.2003.10.005.

Thompson, I.D., Mackey, B., McNulty, S., Mosseler and Alex (Eds.) (2009) *Forest resilience, biodiversity, and climate change: A synthesis of the biodiversity / resilience / stability relationship in forest ecosystems*. Secretariat of the Convention on Biological Diversity: Montreal.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G. and Gaston, K.J. (2007) Urban form, biodiversity potential and ecosystem services. *Landscape and Urban Planning*, 83(4), 308–317. Available at: doi:10.1016/j.landurbplan.2007.05.003.

Trepl, L. (1995) Towards a theory of urban biocoenoses, 3–21.

Trowbridge, P.J. and Bassuk, N.L. (2004) *Trees in the urban landscape: Site assessment, design, and installation*. Wiley: Hoboken, N.J.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W. and Christensen, L. *et al.* (2003) A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14), 8074–8079. Available at: doi:10.1073/pnas.1231335100.

Tyrväinen, L., Pauleit, S., Seeland, K. and Vries, S. de (2005) Benefits and Uses of Urban Forests and Trees, 99, 81–114. Available at: doi:10.1007/3-540-27684-X_5.

Vale, L.J. and Campanella, T.J. (2005) *The resilient city: How modern cities recover from disaster*. Oxford University Press: New York.

van Geel, M., Yu, K., Peeters, G., van Acker, K., Ramos, M. and Serafim, C. *et al.* (2019) Soil organic matter rather than ectomycorrhizal diversity is related to urban tree health. *PloS One*, 14(11), e0225714. Available at: doi:10.1371/journal.pone.0225714.

van Kleunen, M., Weber, E. and Fischer, M. (2010) A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology Letters*, 13(2), 235–245. Available at: doi:10.1111/j.1461-0248.2009.01418.x.

Wagner, M.M. and Gobster, P.H. (2007) Interpreting landscape change: Measured biophysical change and surrounding social context. *Landscape and Urban Planning*, 81(1-2), 67–80. Available at: doi:10.1016/j.landurbplan.2006.10.019.

Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S. and Schultz, L. (2006) A Handful of Heuristics and Some Propositions for Understanding Resilience in Social-Ecological Systems. *Ecology and Society*, 11(1). Available at: doi:10.5751/ES-01530-110113.

Walker, B., Holling, C.S., Carpenter, S.R. and Kinzig, A.P. (2004) Resilience, Adaptability and Transformability in Social-ecological Systems. *Ecology and Society*, 9(2). Available at: doi:10.5751/ES-00650-090205.

Yan, Z., Teng, M., He, W., Liu, A., Li, Y. and Wang, P. (2019) Impervious surface area is a key predictor for urban plant diversity in a city undergone rapid urbanization. *The Science of the Total Environment*, 650(Pt 1), 335–342. Available at: doi:10.1016/j.scitotenv.2018.09.025.

Zang, S., Wu, C., Liu, H. and Na, X. (2011) Impact of urbanization on natural ecosystem service values: a comparative study. *Environmental Monitoring and Assessment*, 179(1-4), 575–588. Available at: doi:10.1007/s10661-010-1764-1.