Trees, Forests and People 8 (2022) 100252

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Research Article

Effects of heat and drought stress on the health status of six urban street tree species in Leipzig, Germany

Dagmar Haase[a,b,*], Rebecca Hellwig[a]

[a] Humboldt University Berlin, Institute of Geography, Rudower Chaussee 16, 12489 Berlin Germany
[b] Helmholtz Centre for Environmental Research – UFZ, Department of Computational Landscape Ecology, Permoser Straße 15, 04318 Leipzig Germany

A R T I C L E I N F O

Keywords:
Heat
Drought stress
Street trees
Damage
Crown defoliation
Climate change
Mapping
Leipzig

A B S T R A C T

Trees are one of the most important elements of green infrastructure in cities. Climate change is specifically affecting trees in many European cities. Trees are experiencing negative impacts from the increase in heat waves and droughts, both of which begin, in some cases, early in the year and continue through the growing season. Current studies on the regionalization of climate change indicate that important water reservoirs such as soil and tree canopies have been drying out for years/decades, and these impacts can be observed in various parts of Europe. Trees react to stress as they age through mechanisms such as crown defoliation, early wilting, shedding of branches and, ultimately, lowered resistance to pests. As a result, massive tree death, both in park trees and street trees, can be observed in many cities. The present study provides a current inventory of street tree damage caused by heat and drought in the city of Leipzig, Germany, in 2020, the third extreme dry year after 2018 and 2019. The field maps focus on different age groups of *Quercus, Tilia, Aesculus, Platanus, Fraxinus* and *Acer* along a periurban-urban gradient. The results are clear: significant damage was found in all tree species. Older trees and newly planted trees are most likely to die as a result of extreme conditions, while younger trees with narrow trunks and crowns that have not yet expanded cope better with both heat and drought. Four out of five mapped street trees showed recognizable damage, indicating severe impacts of climate change on important elements of green infrastructure in cities.

Introduction

Street trees are essential elements in the network of urban green infrastructure in cities and significantly contribute to urban quality of life (Pauleit et al., 2018; European Commission, 2012). Due to their fragmented distribution and the small area occupied by single trees, they are not defined in the literature as independent ecosystems but as components of larger ecosystems (Bolund & Hunhammar, 1999). Street trees provide numerous ecosystem services at the local level, including improving air quality by binding CO_2 and aerosols from the air, producing oxygen, and regulating noise and microclimates (Bolund & Hunhammar, 1999; Haase et al., 2014; Salmond et al., 2016; Biercamp et al., 2018; McPhearson et al., 2018). Park and street trees improve urban aesthetics, provide a central urban design function and have a positive influence on the health and well-being of residents (Pauleit et al., 2018). In addition, urban trees represent an important habitat, a source of food and a connection between the individual components of urban green infrastructure for many animal species (McDonald et al., 2019). These trees provide shade in summer, reduce wind speed in winter and thereby reduce energy use (Bolund & Hunhammar, 1999; McPhearson et al., 2018). Due to their multifunctionality, urban trees are an indispensable component in urban planning and an effective nature-based solution for adapting cities to anthropogenic climate change (McDonald et al., 2019; Stadt Leipzig, 2019).

Urban street space is an extremely demanding habitat, and compared to (semi)natural ecosystems, they include many additional stress factors (Schönfeld, 2019). These stresses can hinder the development of trees and reduce their life expectancy (Moser et al., 2015; Brune, 2016). High sealing rates, small tree grates and planting pits, unsuitable tree substrates, compacted soils, reduced gas exchange, space competition, air pollution, nutrient deficiency and the heat island effect are some of the stress factors that affect street trees (Bassuk & Whitlow, 1987; Steinike and Schwab, 2010; Brune, 2016; Schönfeld, 2019). Niinemets & Valladares (2006) highlight further stress factors such as waterlogging due to sealing, soil compaction or heavy rain events and strong shadows due to neighbouring trees or narrow and tall buildings. Injuries from structural

* Corresponding author.
E-mail address: dagmar.haase@geo.hu-berlin.de (D. Haase).

https://doi.org/10.1016/j.tfp.2022.100252
Received 15 February 2022; Received in revised form 1 April 2022; Accepted 5 April 2022
Available online 25 April 2022

measures above- and belowground, collision damage from vehicles, vandalism and soil contamination by urine or pollutants also affect street trees (von Döhren and Haase, 2015). Damage can also be caused by road salt (chloride absorption from the ground) and lead to pathological metabolic disorders (Schönfeld, 2019).

The increase in global average temperatures caused by anthropogenic climate change, changes in the precipitation balance and the increase and intensification of droughts, storms and extreme weather events due to the increase in greenhouse gas concentrations in the atmosphere can intensify the existing stress factors for urban trees because these factors directly lead to a lack of water and heat and indirectly promote pests and diseases (Gillner et al., 2014; European Environment Agency, 2017; Hoegh-Guldberg et al., 2018; Thober et al., 2018). The urban heat island effect increases with rising temperatures and can further exacerbate heat and drought stress and favour heavy rainfall events (Schwarz et al., 2012; European Environment Agency, 2017). Since soil can lose its ability to absorb and store water when heavily sealed and compacted, the largest proportion of water flows off the soil surface after heavy rainfall and is no longer available to trees for uptake via their roots (Dickhaut et al., 2019). Direct surface runoff increases the degradation of the soils further, as well as the risk of superficial flooding, and at the same time, this process leads to a lowering of the groundwater level. With rapid runoff, essential nutrients are flushed out of the soil (ibid.), and this process weakens tree health and can significantly reduce resistance to stress factors such as storms or pests (Bolund & Hunhammar, 1999).

Stressed trees have a higher susceptibility to diseases, parasites and insects, whose spread and reproductive success will be amplified by rising temperatures in the future (Böll et al., 2014 and 2018). The intensity and number of stress factors occurring at the same time influence the degree of loss of vitality and can vary greatly within a genus or a species as well as between species (Gillner et al., 2014; Duthweiler et al., 2017). With decreasing tree health, their potential to provide ecosystem services decreases (Bolund & Hunhammar, 1999; Haase et al., 2014). Healthy trees are therefore extremely important for healthy and climate-resistant cities (Lin et al., 2021), but they require a high level of resistance and adaptability to climate and soil conditions to survive in the urban environment.

While research and public interest in Europe have long focused predominantly on trees in natural ecosystems and forests and there are a large number of studies investigating the effects of climate change on forests (Kölling & Zimmermann, 2007; adelphi/PRC/EURAC, 2015, BfN, 2020; Allen, 2010a; Grundmann et al., 2009), to date, studies of direct climate change effects on trees in urban areas and, in particular, heat and drought are not widely available (Duthweiler et al., 2017; Giller et al., 2014; Pretzsch et al., 2017; Böll et al., 2018). The first long-term studies of street trees were carried out across Germany in the mid-1990s (GALK street tree tests, “City trees in climate change SiK”, *KlimaArtenMatrix für Stadtbaumarten KLAM-Stadt, Projekt Stadtgrün* 2021), and these studies explored the ecological suitability of street trees (Roloff et al., 2008; Böll et al., 2014; Dickhaut et al., 2019; GALK, 2012: Cooperation project on behalf of the BMU, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety between the University of Hamburg, the Authority for Environment and Energy of the Free and Hanseatic City of Hamburg and the HafenCity University Hamburg, Dickhaut et al., 2019, as well as the project of Bavarian State Institute for Viticulture and Horticulture, Böll et al., 2014). The city of Leipzig in eastern Germany has also participated in such programmes, from 1995 to 1999 and since 2005, in various GALK (German Garden Office Managers’ Conference) street tree test programmes. The first results from these test series and the assessment of single tree species examined in the GALK studies regarding tree species’ ability to resist heat and drought were used as a reference for this study. In the GALK studies, tree species were primarily examined for growth performance, location requirements, drought and heat tolerance and winter hardiness, namely, sensitivity and tolerance to frost and the risk of late frost (GALK, 2012).

However, species-specific demands in regionally varying locations in cities, the reactions of street trees to various biotic and abiotic influences, and small-scale climatic conditions have not been sufficiently studied, which is why further investigations to provide more substantial planning support are urgently required (Roloff et al., 2008; McDonald et al., 2019). As many different species as possible and their respective reactions to stress events should be examined so that biodiversity can be comprehensively considered when selecting suitable street trees for the future–because in comparison to other stands, a species-poor tree stand with low genetic diversity is more susceptible to disturbances and pests and can increase the risk of tree death (GALK, 2009; Böll et al., 2018). Further field studies, test programs and accounts of experiences from tree nurseries are necessary to obtain applicable data on the effects of climate change on the state and health of street trees. These data will be of particular importance for green space managers and city planners in large cities such as Leipzig and throughout Europe to carry out long-term and sustainable street tree plantings. Ultimately, only a healthy and dense canopy will guarantee the resilience of any city under ongoing and increasing climate change (Egerer et al., 2021; Lin et al., 2021).

The study presented in this article conducted a pilot test to detect the effects of heat and drought stress on both the state and health of urban street trees in the city of Leipzig. Based on sampling from June to August 2020, the damage to and current health state of six representative and dominant tree species were mapped and evaluated: maple (*Acer*), horse chestnut (*Aesculus*), ash (*Fraxinus*), plane tree (*Platanus*), oak (*Quercus*) and lime tree (*Tilia*). The species mapped and examined each account for >2.5% of the total tree population and together make up more than 75% of the population (Table 2).

The aim of this study was to identify tree species that are in good health and comparatively resistant to drought and heat as well as other tree species that are not. Species and age classes particularly affected by damage were determined to identify determine tree selection for planting in the future. Using visual inspection, we assessed the condition of the trees. Both the number and intensity of the stress factors typically indicating heat and drought stress were identified. Furthermore, we cross-checked confounder variables of tree stress to exclude other impacts on street tree health. The degree of soil sealing was used as a proxy in this case.

The following research questions and hypotheses were established:

1 Of the six tree species investigated, which age classes are in poor health and which externally visible features indicate heat and drought stress that can be documented and with what frequency in the field study?
2 Were trees with declining health states found at the study sites exhibiting a high degree of impervious cover?

The null hypothesis *H*01 assumes that all trees examined would show a large amount of damage and poor health, regardless of their age. The alternative hypothesis *H*11 assumes that only trees in the age class of old trees planted before 1970 would show large amounts of damage from heat and drought and thus be in poor health. The null hypothesis *H*02 for the location assumes that the degree of sealing would have no influence on the health of the street trees. The alternative hypothesis *H*12 assumes that tree health would deteriorate with increased sealing.

Materials and methods

Study area under climate change

The city of Leipzig is located in eastern Germany in the federal state of Saxony. The urban area covered 297.8 km^2 and had a total of 602,000 inhabitants in 2020 (Statistical Offices of the Federal Government and the States, 2020). Leipzig belongs to the Halle-Leipzig lowland bay transition area in a more continental to a generally maritime climate zone, an important climate type in Central Europe. Leipzig has a moderate climate with warm summers and cool winters (Steinike and Schwab, 2010). The annual mean temperature is 9.7 °C, with January being the coldest month with an average daily temperature of 0.2 °C and July being the warmest month of the year with 19 °C. With an average annual precipitation of 512 mm, the city has a limited water budget, with winter having significantly less rainfall than summer. The driest months are May to August, and the wettest months are usually January, February, and October (Deutscher Wetterdienst (DWD), 2021). As the Halle-Leipzig lowland bay is located on the leeward side of the Harz Mountains in the west, the northwestern part of the city area receives less precipitation on average than the southeastern part (Müller, 1999). Whether this precipitation difference has a specific effect on the vitality of street trees across the city remains an open research question. However, attention should be placed on the fact that this precipitation variability within the urban region might become more pronounced in times of increasing climate change (Lin et al., 2021).

The Federal Statistical Office calculated the settlement and traffic area at 54.5% (of which, the traffic area only is 12.1%) of the total land area in Leipzig in 2019, which means that the city already has a high degree of sealing (Statistical Agency and Land Cadastre, 2021). Approximately 64% of the existing traffic area offers potential for new roadside plantings, as these areas do not have plantings or only are patchily planted (City of Leipzig, 2019). Thus, the city presented a comprehensive street tree concept for 2030 in 2019, in which street trees are mentioned as a fundamental element of green infrastructure and an important measure for adaptation to climate change in Leipzig (ibid.).

The selected study area (Fig. 1) extends over a length of approximately 12 km and a width of 2.6 km from the local district of Wiederitzsch in the north through the city centre around the Central train station to the Connewitz Kreuz in the south of the city. The study area covers 30 km^2. The mapped street trees mapped occur in all 14 local districts. The northernmost mapped point is approximately 8 km from the city centre, and the southernmost mapped point is approximately 3 km from the city centre. The characteristics of the study sites differ greatly from one another: The city centre of Leipzig is characterized by a high sealing rate and a very dense built-up area with mostly four- to five-story buildings, with occasional smaller green areas and parks. The limited open space allows for only a limited and fragmented number of street trees with small tree trunks. Larger green spaces are minimally available. The southern suburb (Südvorstadt) and northern Connewitz are also densely populated with 4–5 story residential housing areas with surface sealing rates of 60–80%. Additionally, in the southern part of the study area, there are only a few connected tree areas and green strips along the streets. In a northerly direction, the building density decreases continuously towards the city limits. In the areas near the outskirts of the city, single and multifamily houses as well as allotment gardens are the dominant land uses. The sealing rate is low on average here, and the roads are often accompanied by wide, species-rich green strips. Beyond the city limits, species-rich meadows and arable land occur along the roads (see Fig. 1).

In recent years, an increase in average temperatures and a deviation from the long-term mean temperature of 9.7 °C (in the reference period 1981–2010) have been observed (City of Leipzig, 2020). In 2014, the annual average temperature was 11 °C, which means a deviation from the long-term mean of +1.3 °C. In 2018 and 2019, the long-term mean increased to 11.2 °C, which is a deviation of +1.5 °C (ibid.). In 2020, the annual mean temperature reached a maximum value of 11.3 °C and a deviation from the long-term mean of +1.6 °C (Deutscher Wetterdienst (DWD), 2021), which means that it exceeded the 1.5- °C target of the international Paris climate treaty of 2015. The regional climate atlas of Germany calculated the greenhouse gas scenario RCP8.54 in Saxony showing a possible mean change in the average air temperature of +2.1 °C by the middle of the 21st century (Helmholtz Association, 2021). The emission path of the greenhouse gas scenario RCP8.5 leads to a high concentration of greenhouse gases (scenario references are from the driving global model CanESM2 and the regional climate model SMHI RCA4 (EUR-44)) (Helmholtz Association, 2021). Hot days with temperatures above 30 °C have increased in recent years (Deutscher Wetterdienst (DWD), 2021). An increase in heat waves and the number of

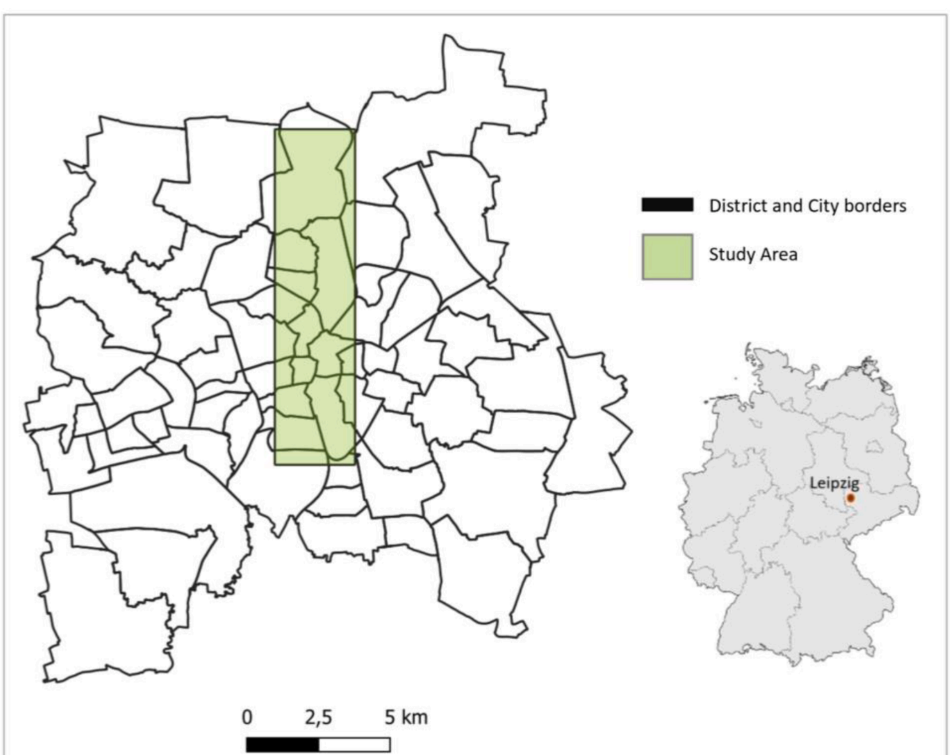


Fig. 1. Location of the study area in Leipzig, Germany, and the mapped transect within the city from the north to the central south (green rectangle).

droughts as well as their intensity in summer are part of the weather (local climate) forecast for this century (EEA, 2017).

Dramatic changes can also be observed in the regional water budget. In 2018, with 338 mm, and in 2019, with 397 mm, the annual precipitation amounts in Leipzig were already far below the long-term average of 511 mm (City of Leipzig, 2020). For the spring and summer seasons in 2020, the drought monitoring at the Helmholtz Centre for Environmental Research showed extreme to extraordinary drought in both the topsoil and subsoil (up to 1.8 m depth; Marx, 2021). A drought occurs when the soil moisture index falls below the 20th percentile, i.e., as low as in only 20% of the cases in the 65-year comparison period (ibid.). The lack of spring season precipitation in April and May ensured that at the beginning of the year, the soil had a low level of soil moisture compared to the long-term mean (determined for 1951–2015), although the precipitation levels in February and the first half of March were above average (DWD, 2021). Precipitation was particularly low in the second half of March and April (ibid.). June and July were also characterized by drought and experienced significantly less rainfall than that in the comparison period (ibid.). A dry day can also be defined as a day with a precipitation level <1 mm, and a drought can be defined as a period of at least five consecutive days with a precipitation level <1 mm (Brune 2016). As a result of this precipitation dependency, the groundwater level dramatically declined, and the groundwater reserves possibly were not replenished to sufficient levels to be available to the trees in the event of drought. Therefore, we assume that in the last few years, the mapped trees had to withstand several years of drought and heat stress and less tolerant and resistant tree species were particularly damaged.

Tree profiles

The tree species selected for the field study are shown in Fig. 2 and introduced in the following paragraphs. Particular emphasis is placed on heat and drought tolerance; however, other properties described in the literature, such as frost tolerance, soil requirements and pest or disease pressure, are also included in the descriptions.

Acer

Nine different species of the genus *Acer* occur in the city of Leipzig, and of these species, field maple (*A. campestre*), Norway maple (*A. platanoides*), sycamore maple (*A. pseudoplatanus*), ash maple (*A. negundo*) and, according to more recent plantings, French maple (*A. monspessulanum*) were considered in this study; the latter two species are not originally native to Central Europe (Roloff et al., 2008). The stock of Norway maples is supplemented by the subspecies 'Apollo', 'Fairview', 'Farlake's Green', 'Olmstedt' and 'Cleveland'. The stock of *Acer* is dominated by Norway maple, which accounts for the largest proportion of *Acer*. Maples reach heights of up to 11 (French maple), 20 (field maple) or 30 metres (Norway maple) and a maximum age of 150 (field maple), 180 (Norway maple) or 500 years (sycamore maple) (GALK, 2012). In comparison to sycamore maple, Norway maple is more resistant in terms of both heat tolerance and drought tolerance (Brune, 2016). The different *Acer* species have different soil requirements: *A. platanoides* is the most undemanding, whereas *A. pseudoplatanus* is more unique with significantly higher water and nutrient requirements and is sensitive to drought (ibid.). *A. pseudoplatanus* does not grow well in dry, wet and acidic soils and often shows growth deficits and premature ageing in such locations (GALK, 2012). *A. platanoides*, on the other hand, still shows good growth performance in dry locations but reacts sensitively to soil sealing (ibid.). *A. campestre* (ibid.) is tolerant to soil sealing. Norway maple has a slightly lower drought tolerance than that of the field and ash maple in the KLAM and is rated as suitable for this category (Roloff et al., 2008). Sycamore maple is classified as having only very limited suitability in terms of drought tolerance but rated suitable in the winter hardiness category (ibid.). *A. campestre* and *A. negundo* are considered warm-loving and are classified as very suitable in terms of both drought tolerance and winter hardiness (ibid.). Finally, the Mediterranean *A. monspessulanum* is classified as very suitable in the drought tolerance category; it is rated suitable for the winter hardiness category (ibid.). Similar to *A. campestre*, this species feels prefers more northern regions in dry and warm locations (GALK, 2012).

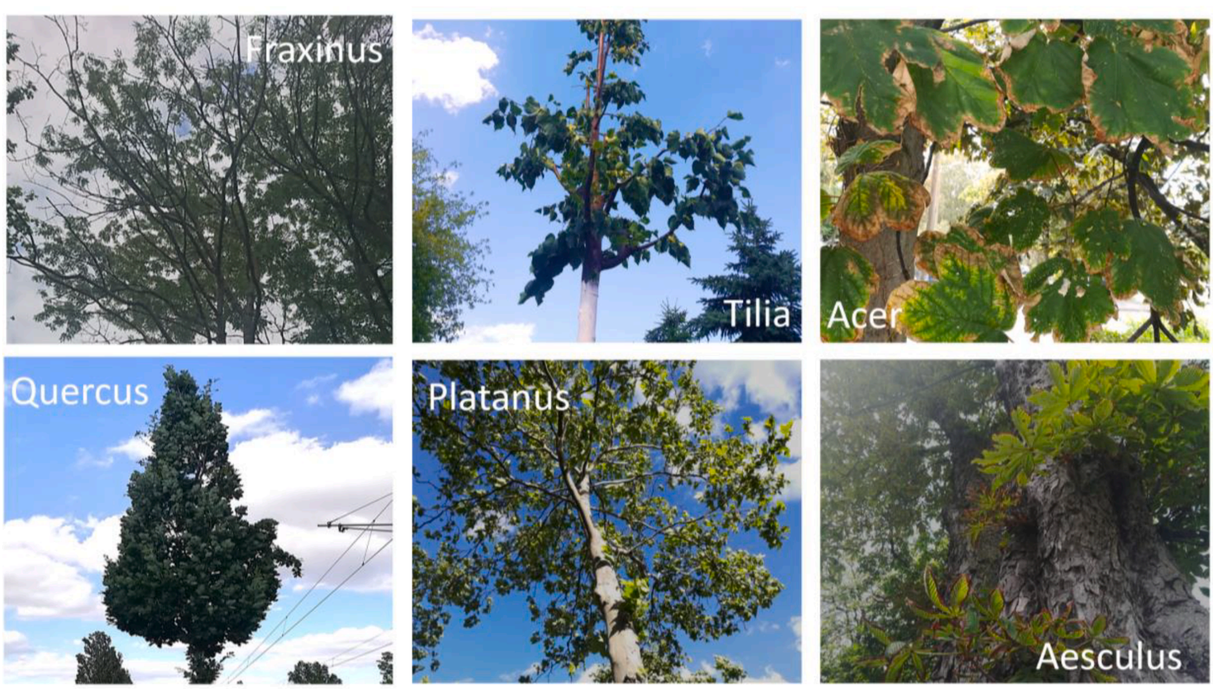


Fig. 2. Tree species studied.

Aesculus

The common horse chestnut (*Aesculus hippocastanum*) is from the soap tree family (Sapindaceae) and is native to southeastern Europe (Ravazzi & Caudullo, 2016). It has a broad range but prefers warm and humid locations (Brune, 2016). Horse chestnut can live for several hundred years, reach heights of 25 to 30 metres and have a trunk thickness of up to 2 metres (GALK, 2012). The crown is broad (cloudy) with thick, strong shoots and branches and leaves with a large area; thus, under healthy conditions, this tree casts enormous shadows and ahs a noticeable cooling effect, which makes horse chestnut particularly popular as a street and park tree (Ravazzi & Caudullo, 2016). Due to its deep and far-reaching roots, horse chestnut is classified as storm-tolerant (Roloff, 2005). Flowering takes place from the end of April to the beginning of May, with more than 1000 inflorescences developing in large, older trees, which is why it is also an important species for bees (ibid.). *A. hippocastanum* is shown to be intolerant of road salt (GALK, 2012). Further stress factors include the increased occurrence of harmful organisms such as the chestnut leaf miner (*Cameraria ohridella*), bacteria (*Pseudomonas syringae pv. Aesculi*) or various fungi and fungus-like organisms that make the tree more susceptible when it is weakened (ibid.). If a chestnut leaf miner infests a tree, then up to 90% of the leaves can be damaged and die; however, the tree can recover after such an attack (Brune, 2016). The typical brownish, elongated pattern on the leaves can be easily distinguished from signs of damage caused by heat and drought (Fig. 2). According to Werres & Wagner (2015), horse chestnut shows symptoms and symptom complexes similar to those that occur under heat and drought stress (sparse leaves, shoot and branch death) when they are attacked by a wide variety of fungal and bacterial species or have secondary infections caused by wood-destroying fungi. Horse chestnut is classified in the KLAM as drought tolerant but only to a very limited extent, which indicates a low level of resistance when there is a lack of water and prolonged periods of drought (Roloff et al., 2008). This species is classified as suitable in the winter hardiness category (ibid.). In the GALK street tree list, *A. hippocastanum* is rated as suitable with restrictions for planting in urban street areas (GALK, 2012). The risk this species faces from complex diseases caused by a large variety of stress factors increases the risk of its failure given the urban climatic conditions expected in the future (GALK, 2012; Brune, 2016).

Fraxinus

Ash trees are native to a large part of the temperate climate zone in Europe, with the common ash (*F. excelsior*) having the largest distribution area (Beck et al., 2016). In the Leipzig study area, ash (*F. excelsior*), flower ash (*F. ornus*) and narrow-leaved ash 'Raywood' (*F. angustifolia* 'Raywood') are common. The conditions tolerated by ash trees are very diverse, and they can withstand moisture and temporary flooding as well as temporary drought; however, persistent waterlogging and strong soil compaction are not tolerated (Beck et al., 2016). Overall, they have a broad distribution but prefer nutrient-rich soils, and their locations can be limited by the pH value of the soil, which should not be below 5.5 since acidic soils are not suitable (ibid.). Damage to ash shoots (fungal infection), which has been widespread since the 1990s, leads to bark necrosis, severe crown defoliation and, in most cases, death in infected ash trees (ibid.). *F. excelsior* reaches heights between 20 m and 35 m and typically has a conical crown (Beck et al., 2016), and this species has a very high light requirement at maturity (ibid.). It prefers fresh to moist soils with a high nutrient content and good water infiltration (Dobrowolska et al., 2011). *F. excelsior* is rated as suitable in the GALK street tree list but with restrictions, as it reacts sensitively to soil compaction (GALK, 2012). In the KLAM assessment, the common ash is classified as suitable in the categories of drought tolerance and winter hardiness (Roloff et al., 2008). The narrow-leaved ash, native to southern Central Europe as far as the Caucasus, reaches a maximum height of 20 m (Caudullo & Housten Durrant, 2016). In the north, the range of this heat-loving species is mainly limited by its sensitivity to frost (GALK, 2012). As a result of climate change, the conditions in regions further north could be improve for this tree, and their range may expand. The crown of the narrow-leaved ash is leafy and dome-shaped but becomes increasingly loose with age (GALK, 2012). *F. augustifolia* prefers calcareous, moist, and loose soils with a pH value of 5–8 as well as mild climatic conditions and rainfall between 400 and 800 mm (Caudullo & Houston Durrant, 2016; GALK 2012). *F. augustifolia* 'Raywood' is described as urban climate-resistant species, tolerant of heat and temporarily dry ground (GALK, 2012). Flower ash (*F. ornus*), which is from the Mediterranean region, is also increasingly establishing itself in Germany (Brandes, 2006). It is a relatively small species and reaches a maximum height of 15 m (GALK, 2012). *F. ornus* does not require a high soil quality and, due to its sub-Mediterranean origin, is well adapted to areas with dry summers and is also less susceptible to ash dieback (Wallmann & Stingl, 2011). Flower ash is rated as very suitable in the drought tolerance category but is only suitable to a very limited extent in the winter hardiness category (Roloff et al., 2008).

Platanus

In the genus *Platanus*, only the maple-leaved plane tree (*P. x acerifolia*) occurs in the study area, so only this species is presented below. It is a deciduous tree that grows to 20 to 30 m in height, and it is widespread in Central Europe and is often planted as a street and park tree in cities (Benning, 2021). Its beige to grey–brown bark flakes off extensively, creating a characteristic pattern on the trunk and branches (ibid.). When older, the trees have a broad and spreading crown with, in some cases, low-hanging strong branches (GALK, 2012). *P. x acerifolia* is commonly used in urban areas because of its minimal requirements; robustness; resistance to air pollution, exhaustion of gases and pathogens; and air pollutant fixation due to its large leaves (Salmond et al., 2016). *P. x acerifolia* has a high need for light and therefore prefers sunny locations on sandy to loamy soils (Benning, 2021). This plane tree seals itself off quickly, so in comparison to species that slowly seal themselves, such as horse chestnuts, it also tolerates injuries from wind breakage or injuries from pruning, construction work or damage from traffic accidents better (Salmond et al., 2016). An increase in pest infestations has been observed in recent years (GALK, 2012).

Quercus

In Leipzig, the common oak (*Quercus robur* L.), the subspecies *Q. robur* 'Fastigiata Koster' and Hungarian oak (*Quercus frainetto*) are the most frequently observed oak species. The English oak usually has a wide, conical crown and sometimes reaches heights over 40 m and an age of over 1000 years (Eaton et al., 2016). This species is native to Central and Southern Europe, widespread across the entire continent and particularly well adapted to the Atlantic and sub-Mediterranean climate, but it also grows well in the region when compared to other oak species in continental and oceanic climates (ibid.). Locations with high levels of solar radiation and nutrient-rich and moist soils are preferred, but the English oak has a broad distribution and tolerates wet soils and flooding in addition to temporary droughts (Gillner et al., 2014). Due to it being a deep-rooted oak, the pedunculate oak is a stable tree that is protected from windthrow and can also reach water from deeper layers in the event of prolonged drought, but a lowering of the groundwater level can be followed by a drought (GALK, 2012; Eaton et al., 2016). Under optimal growth conditions, it has a high ability to sprout again; thus, under favourable conditions, it has a good ability to recover after stress events (Eaton et al., 2016). The GALK street tree list indicates the pedunculate oak is suitable with restrictions (GALK, 2012). In comparison to *Q. robur, Q. robur* 'Fastigata Koster' grows to 20 m in height, has a slimmer crown shape and more compact growth, and it is suitable as a street tree (ibid.). Hungarian oak (*Q. frainetto*), which originates from the Mediterranean region, has low nutrient demands and grows in acidic and dry to sometimes waterlogged locations (Mauri et al., 2016). It grows in the transition zone between the Mediterranean and the continental climate and is therefore more drought-tolerant but also less frost-hardy than other oak species (ibid.). *Q. frainetto* reaches a maximum age of 200 years and up to 30 m in height (ibid.). It has been in the GALK street tree test 2 since 2005, and it is considered urban climate-resilient and suitable with restrictions (GALK, 2012). Due to its drought tolerance, the subspecies *Q. frainetto* 'Trump' is currently also being examined for its suitability as an urban tree in the Urban Green 2021 project (Böll et al., 2018). In tests, this species has been shown to be resistant even under drought conditions and without additional watering, and it rarely showed signs of drought stress even under harsh conditions (ibid.).

Tilia

The two native species winter lime tree (*T. cordata*) and summer lime tree (*T. platyphyllos*) are the most common species in Leipzig, and in particular, *T. cordata* is a very popular street tree due to its adaptability (Schönfeld, 2016). The data on the genus *Tilia* are mainly related to the species *T. cordata* and its subspecies. The two subspecies *T. cordata* 'Rancho' and *T. cordata* 'Green Spire' are represented in Leipzig, which were also examined for their suitability in the GALK street tree tests (GALK, 2012). Winter lime trees are large trees that reach heights of up to 30 m and crown widths of up to 8 m (Dörken & Fig. 7: old specimen of a winter lime tree (*T. cordata,* planted in 1930) with a crown consisting entirely of reiterations, probably because of a cut back through the stone corner, 2017). These trees can live for several hundred years using numerous survival strategies (rejuvenation through the formation of secondary roots in the interior of a hollow trunk) (ibid.). The location requirements and amplitudes of the various lime tree species differ greatly, with the summer lime tree having significantly higher demands of its habitat (e.g., soil quality and moisture) than those of the winter lime tree (GALK, 2012; Schönfeld, 2016). *T. cordata* is broadly distributed and grows in weakly acidic to alkaline, calcareous, and nutrient-rich soils but also tolerates moderately dry to fresh soils (Schönfeld, 2016). Specifically, at a young age, it is shade-tolerant and therefore has an advantage over other species in the city when there is increased shade (Dörken and Steinecke, 2017). After stress events, this tree should have sufficient sunlight available for recovery (ibid.). A shady location can also affect and increase its height but can reduce its broad growth (ibid.). Schönfeld (2016) indicated a strong intolerance to road salt, which manifests itself in polluted locations in the form of leaf margin necrosis. Lime trees have a high ability to recover from stresses, as they can develop tree suckers (new shoots from buds on the trunk or stumps) from which the entire crown (secondary crown) may grow (Radoglou et al., 2008). In the KLAM, *T. cordata* is classified as suitable in the drought tolerance category and as very suitable in the winter hardiness category (Roloff et al., 2008). Summer lime tree is rated as problematic in the KLAM in the drought tolerance category but as good in the winter hardiness category; therefore, it is rated as suitable in this category (ibid.). In the GALK street tree list, it is described as unsuitable and not tolerant of the urban climate (GALK, 2012). The Dutch lime tree (*T. x vulgaris*) is classified as problematic in the drought tolerance category and, similar to the summer lime tree, it is therefore only conditionally suitable as a street tree according to the KLAM (Roloff et al., 2008).

Damage model

Drought tolerance

Drought stress is cited as one of the most common stress factors for street trees in a city (Brune, 2016). This stress type occurs mainly when the evaporation pressure of a tree increases due to high temperatures, strong sunlight and low air and soil humidity (ibid.). A heavily sealed site can promote and intensify drought (Dickhaut et al., 2019). A lack of water can reduce plant productivity and lead to closure of the leaf stomata to avoid further loss of fluid, which reduces the carbon uptake and thus the photosynthetic activity of the tree (Thober et al., 2018). This process can disrupt a tree's metabolism and water balance and lead to damaging reactions in leaf cells (Dickhaut et al., 2019). In comparison to less adapted species, drought-adapted species are capable of decoupling transpiration from atmospheric influences and maintaining transpiration longer when there is a water deficit (Duthweiler et al., 2017). However, if water pressure between the roots and the crown cannot be maintained due to a lack of incoming water and the suction power of the roots is insufficient to absorb water, then this scenario leads to a supply deficit in the small new shoots in the outer area of the crown (Brune, 2016; Dickhaut et al., 2019). Smaller shoots and leaves–that of young and freshly planted trees–are therefore first thrown off during drought stress to reduce the surface area and reduce transpiration (Brune, 2016).

A lack of water can also cause a tree to form extensive new roots outside of the planting hole created for it to obtain water and nutrients. A flattened top shoot is a clear indication of this scenario (Hoffmann, 2008; Mullaney et al., 2015). Based on drill core data, growth deficits can be traced back to periods of drought stress, which were stronger for species that are not drought tolerant than for drought-tolerant ones (Duthweiler et al., 2017). It has been shown that shoot growth during and after drought can be reduced in favour of root growth so that the roots can spread and obtain new water sources (Böll et al., 2018). During the growing season, in particular, water shortages can shorten the development time (Thober et al., 2018). If trees are regularly exposed to drought stress in consecutive years, then mortality can increase (Brune, 2016). As stated above, the species of interest in this study showed very different tolerance ranges and adaptation strategies to drought stress and survived in periods with little water (ibid.).

Heat stress

Due to the high density of buildings, complex surfaces and three-dimensional structures, the resulting reduced wind speed, and the higher heat storage capacity of large materials such as cars, buildings and roads, cities warm significantly more than the rural environment, and this warming can create a very hostile microclimate for street trees (Alavipanah et al., 2018; Bolund & Hunhammar, 1999). The orientation of a street, the height of surrounding buildings, and thus the intensity of direct solar radiation influence the air temperature in the area around a tree as well as the surface temperature of tree bark and the humidity of leaves (Brune, 2016). Leipzig's dominant tree species differ greatly in their abilities to cope with heat stress, which, amongst other factors, depends on species-specific adaptation strategies such as morphological and physiological processes and characteristics such as colour, shape, size and hairiness of the leaves (Roloff et al., 2008; Brune, 2016). At high air temperatures, the atmosphere can absorb more water, which increases evaporation from the land surface (Thober et al., 2018). This process further increases the vapour pressure deficit in the air, i.e., the difference between the saturation vapour pressure and the actual vapour pressure in the atmosphere (Grossiord et al., 2020). To prevent overheating of a leaf surface, it is cooled by transpiration, a process by which a leaf is stimulated to increase evaporation capacity, which increases the water requirement of the tree (ibid.). At the same time, a tree experiences negative impacts from a lack of water, while its transpiration capacity decreases as its stomata are closed. In turn, this sceanrio reduces or even stops the natural cooling of the leaf surface (Brune, 2016). As a result, leaves can overheat when exposed to strong solar radiation, and burns can occur, e.g., in the form of leaf margin necrosis (brown, burnt edges) or brown spots and discolouration of different areas and dimensions (ibid.). Further signs of heat stress include the curling of the leaves or a change in the position of the leaves to prevent exposure to direct sunlight and to minimize the surface that is exposed to it (ibid.). If too much energy is contained in a tree due to increased solar radiation and it cannot be released again, then trunk cracks, solar necrosis or bark burns can occur (GALK, 2012).

Derived damage model indicators

Before the field study was carried out, the indicators that were used for the on-site, visual inspection were defined to document the damage and to be able to assess the health of the trees under investigation. For this purpose, three typical damage features clearly visible from the outside of a tree and easily detectable without further aids were selected. The focus of the observation was on the crowns of the trees since damage is clearly visible there (Dobbertin et al., 2009). In various studies, the occurrence of leaf damage in the form of curling or deformation, yellowing, drying or leaf necrosis and the death of shoots were significant damage characteristics found in thinning crowns (see here Hoffmann, 2008; Roloff et al., 2008; Dobbertin et al., 2009; GALK, 2012). Dobbertin et al. (2009) classified a tree with a total canopy defoliation of 25% or more as damaged. Furthermore, drooping branches and dead main shoots are clear signs of drought stress (GALK, 2012). Various descriptions and representations from the literature were used as references to determine the severity of the damage (Hoffmann, 2008; Roloff et al., 2008; Dobbertin et al., 2009).

Since the selected damage features were not all cause specific, additional features and characteristics were recorded during the visual inspection, which, when combined, should provide better conclusions about the causes and severity of the observed damage (Dobbertin et al., 2009). An additional increase in the formation of repeated and new shoots on the trunk or base of a trunk can be interpreted as a further sign of stress, as the tree tried to compensate for components that were dead or already been damaged (Hoffmann, 2002). Tree species can develop repeated shoots after stressful events but also have an improved ability to resist and can recover again after stressful events (Ishii et al., 2007; Radoglou et al., 2008).

In the field, it is especially difficult to distinguish precisely whether a harmful characteristic is the cause of drought or heat since both stress factors are mutually dependant and usually reinforce one another (Dobbertin et al., 2009). Therefore, in this study, no explicit distinction was made between damage caused by heat and damage caused by drought, but the indicators serve as the basis for assessing the overall conditions of the trees after two seasons dominated by cooccurring heat and drought. During mapping, a binary coding system was used: “yes” (could be identified/is available) and “no” (could not be identified/is not available). The assigned vitality level (defined later in this section) reflected the severity of the total damage. As a confounder variable, the degree of soil sealing was also mapped to classify the locations into sealing levels (Table 1). The soil sealing rate for a location was based on an estimate of the percentage of sealing in a radius of approximately 20 metres around a street tree. Table 1 lists all indicators of the field mapping damage model and provides some explanations.

Tree selection and age classification

The tree data used in this study were obtained from the street tree cadastral for the city of Leipzig, which has been maintained since 1992 (Stadt Leipzig, 2020). The dataset comprises a total of 60,414 street trees in the entire area of Leipzig, with information on genus, species (and possibly subspecies), location (street and district), and planting year for each recorded street tree. The dataset was used and edited using Geographical Information System QGIS, version 3.12. In the preprocessing step, the six most commonly occurring tree species were selected, and the database was filtered. In addition, a new layer for each genus was created and merged for further use.

All data points for each species were thereafter classified into three different age class categories: young plantings after 2009; medium-old plantings between 1970 and 2009, and old plantings before 1970. The street tree cadastral provides the year of planting. According to a personal communication from the Leipzig Green Space Office, the trees were planted at an age of approximately nine years according to the regulations since the 1990s. Therefore, the year of planting does not give an exact indication of the actual age of the trees; nine-year-old plants are assumed here for the purpose of standardization. The growing conditions in the first years of life of an urban tree, which are often characterised by a high level of maintenance efforts in tree nurseries, are often excellent and thus usually very different from the growing conditions later in the city. New plantings are also subject to regular maintenance in the first few years during their growth and development phase (City of Leipzig, 2019). In the study, therefore, young trees may not yet have shown any visible signs of the effects caused by the new location, as they have a bark protection coating protecting against the bark being heated in direct sunlight (sunburn) and, in addition, they were regularly watered (ibid.). The classification of crown defoliation (see Table 1) was based on a crown transparency analysis according to Hoffmann (2008) as well as on the recommendations of the GALK working group on street trees (2002).

The subdivision of the age classes was based on the “street tree concept 2030 of the city of Leipzig” (2019). A tree is considered to be a young tree until it is sexually mature, here defined as a planting year after 2009 or a maximum age of 20 years (ibid.). In this phase, the tree is considered to be able to react well to external influences (ibid.). In the ripening phase, here referred to as middle-aged plantings, with an age between 21 and 50 years, the tree reaches its final height (ibid.). Dickhaut et al. (2019) identified trees over the age of 40 to be particularly worth protecting, as they have proven to be able to survive and are resistant to stress and external influences; however, the ability to react decreases with increasing age. A tree is considered mature (ageing phase) from an age of approximately 51 years onwards (City of Leipzig, 2019). The scope of the ecosystem services provided increases with age in healthy street trees (Bolund & Hunhammar, 1999). From the ripening phase, pruning is carried out regularly by the Cities' Green Space Office to rejuvenate and protect the crown to promote development (City of

Table 1
Indicators of the damage model used during the field mapping campaign.

Indicator	Type	Explanation
Twig dieback	binary	• No dead shoots recognizable or only a few small ones • Several small and/or large shoots have died
Canopy dedensification	binary	• Crown dense and full of foliage or only a few small bare spots in an otherwise closed canopy • The crown already shows increased and larger leafless gaps, defoliation > 25%
Leaf damage	binary	• Leaves are upright and richly coloured • Leaves curl up, droop, or are already discoloured or dried up
Soil sealing rate	Levels:0 … unsealed1 … <50% sealed2 … 75% sealed3 … 100% sealed	• 10-25% - The area around the tree is not sealed except for a small area such as a road surface • 26-50% - A large part of the area is unsealed (e.g., street to park, between suburban residential areas) • 51-75% - More than half of the surrounding area is sealed in some way, but the tree is in a larger green area • 76-100% - Except for the tree grate, the area around the tree is (almost) completely sealed (e.g., in the city centre)

Leipzig, 2019). The resulting street tree species mapped in this study, classified by age in percent and total number, are given in Table 2.

The percentage of the six tree species examined in relation to the total tree population and in the sample produced in this study is shown in Fig. 3 with a combined pie chart. The share of the six species selected accounts for more than ¾ of the total street tree population, and the genus *Tilia* was the most frequently planted street tree in Leipzig, accounting for more than one-third of the total tree population. The species *Acer* and *Fraxinus* ranked second and third in abundance, respectively. *Quercus, Platanus* and *Aesculus* each only accounted for a small proportion of the total population and are comparatively rarely represented.

For the selection of the sample, the data points of the tree genera were cut to the layer of the study area. These tree species datasets were then subdivided into the three plant categories to select a sample of examination points for the field study. At least 5 examination points were selected from the plant categories for each tree genus. No minimum distance was specified between the individual data points. The points were chosen so that they were as close as possible to being evenly distributed over the study area. This approach ensured that the trees were exposed to different site conditions, which could then be compared. The distribution of the percentages of the species in the sample was more even than that of the total stock, with *Tilia* also having the largest share (Fig. 3).

Most of the mapped trees had 33 data points, whereas only a total of 16 trees were listed in the dataset for *Aesculus* because the selected tree species in the study area differed in frequency and, in some cases, only sporadically. Forty-eight of the 137 trees in the study were classified in the category of young plantings, 50 were classified as medium-old plantings, and 39 were classified as old plantings. The number of plantings was between 1885 and 2019, and the oldest tree in the study was 135 years old. The average age of the whole sample was 39 years.

Field-mapping campaign

From June to August 2020, data on the health of and damage to 137 street trees were collected in Leipzig. The field study consisted of a one-time visual inspection of the trees selected in advance as well as documentation of the trees, with tree characteristics and damage recorded in a database with photos. After the tree location was identified with the aid of the GIS map (Fig. 4) and Google Maps, a brief description of the location and the immediate vicinity was developed and included information on the degree of sealing, approximate tree size, dimensions of the tree slice and any underplantings, traffic and pedestrian traffic, and the density of buildings. When describing the volume of traffic and pedestrians, only the period of visual inspection of the tree at the site was considered. In the second step, the overall tree condition and appearance were determined based on the GALK street tree list, and this information was based on the crown shape (egg-shaped, columnar, conical, or rounded), branching pattern, growth of the main shoot and

Table 2
Street tree species mapped in this study classified by age in percent and total number.

Species	Young trees	Average age	Mature trees	Total	Percent
Acer	847	5,862	1,437	8,146	13.5
Aesculus	89	1,036	452	1,577	2.6
Fraxinus	311	5,586	596	6,493	10.7
Platanus	769	3,516	1,086	5,371	8.9
Quercus	767	1,832	478	3,077	5.1
Tilia	3,332	11,651	6,766	21,749	36
Total per species	*6,115*	*29,483*	*10,815*	*46,413*	*76.8*
Total trees stand Leipzig	**8,338 (13.8%)**	**39,171 (64.8%)**	**12,905 (21.4%)**	**60,414**	**100**

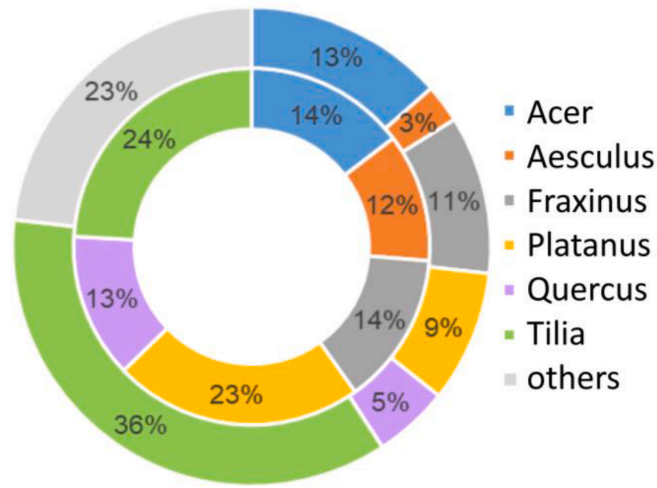


Fig. 3. Composition of the field sample mapped in this study (inside ring) compared to the entire tree stand of Leipzig (outside ring).

trunk (straight, oblique, or twisted), fruit or flower development (present, missing, or reduced), and cultivation of roots. Special features, such as strong cutbacks of the crown, the presence of a water pocket and a protective bark coating, were also documented here. In addition, notes were taken on the condition and appearance of the bark. Characteristics and abnormalities that could be relevant to explaining the state of tree health were also recorded. All 137 individual trees were examined for the previously selected damage characteristics: leaf damage, shoot death and crown defoliation in Table 2.

The first action taken was to check whether any damage features occurred on each tree. If damage was observed, then this was documented in the table with "yes", or if no damage was observed, then this was documented with a "no". If a damage feature was present, then it characteristics were described as precisely as possible. Additional information provided on the damage was not considered in the subsequent calculation but was used for transparency purposes and an explanation of the assigned vitality level (*Vst*). Vitality describes the state of tree health and its survival as well as its respective growth ability (GALK, 2002; Hoffmann, 2008). The vitality levels were divided based on a four-point scale from I to IV as follows and according to Nowotny (2013):

- ***Vst*** I - No or only slight damage: The tree is in very good external condition and has a healthy and full leafy crown; the leaves are erect and a rich green colour without major damage or discolouration; only mild symptoms of stress such as rolled leaves; crown defoliation <10%.
- ***Vst*** II - Moderate damage: The tree shows several damage features; the leaves already look substantially abnormal, for example discoloured or deformed; small shoots and branches are drooping or have already died; crown shows deficits; crown defoliation <25%.
- ***Vst*** III - Severe damage: The tree shows several clearly marked damage features; fine to large branches affected by death; bark is peeling off the branches and trunk or cracked; crown defoliation> 25%; leaves withered or discoloured; leaf fall.
- ***Vst*** IV - Extreme damage or dead - The tree shows all three damage features, larger parts of the tree or the crown are already completely dead, more than 60% of the crown is lost, and the bark is torn open or is peeling off over a large area; total loss.

All damage features were photographed for digital documentation. In the following section, seven examined trees (UB indexed) are used to illustrate how the damage model was applied, how the damage was

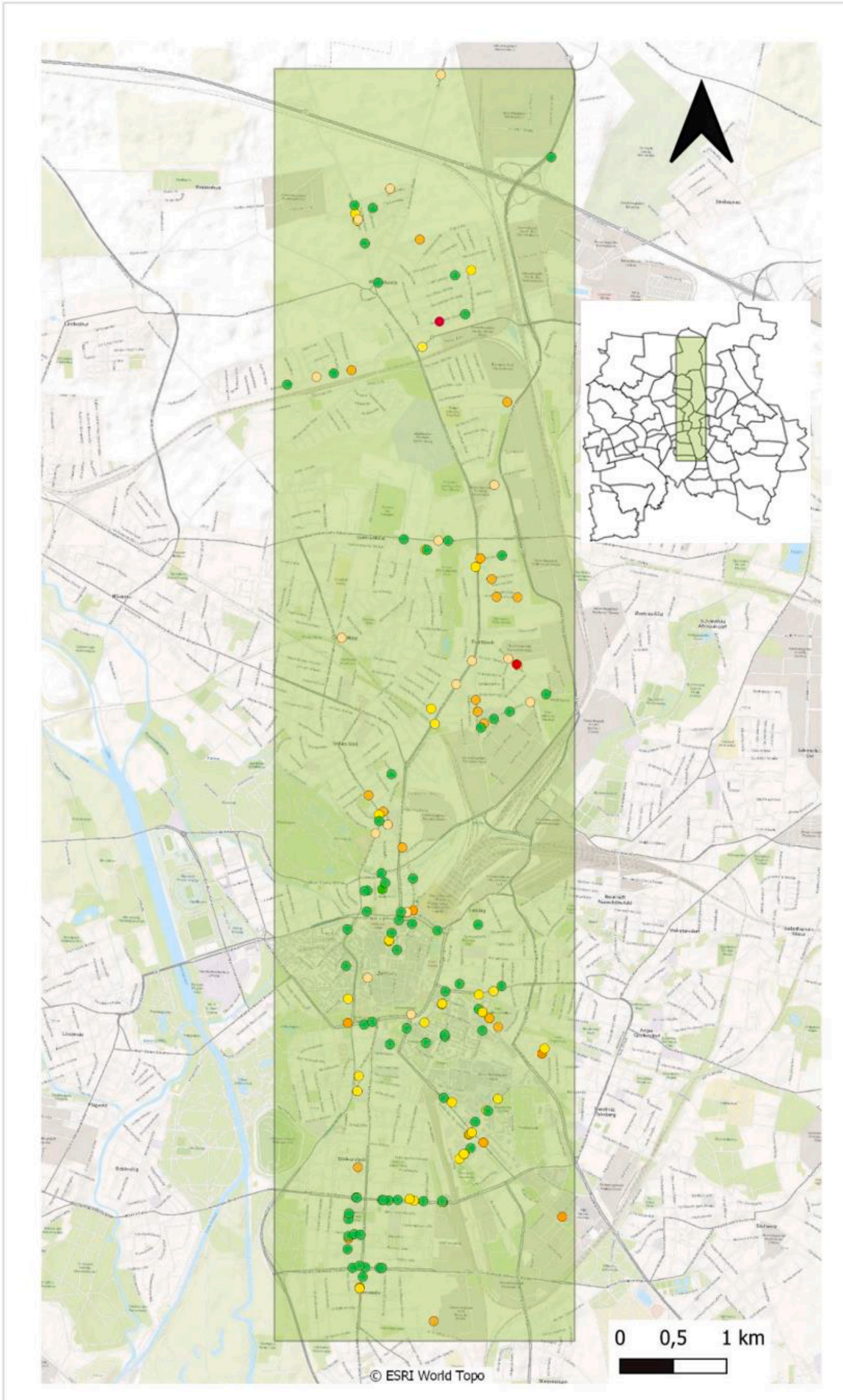
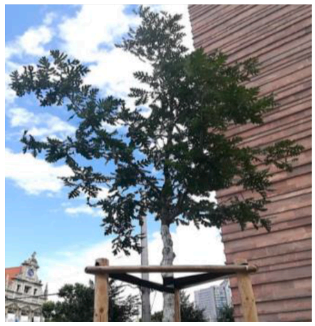


Fig. 4. Map of the periurban-urban gradient of all mapped trees showing their current vitality levels.

documented, and how the state of tree health was classified:

UB11: Hungarian oak (*Quercus frainetto*). Planting year: 2015. Location: Nonnenmühlgasse (centre), high degree of sealing and high traffic and pedestrian * indoor volume, tree slice with a diameter of approx. 3 m, relatively large, covered with gravel and unplanted, construction work being carried out in the immediate vicinity. Species appearance: young tree with upright growth, large, richly coloured leaves and a conical to rounded crown, no fruiting. Shoot death: none but shoots partly drooping. Crown defoliation: none, deficit on one side due to the averse branch. Leaf damage: leaves slightly rolled up. Bark: bark protection coating available, already cracked but mostly covering tree. **VSt**: I.



UB44: Winter lime (*Tilia cordata*). Planting year: 1993. Location: Max-Liebermann-Strasse; four lane road. Avenue character; high volume of traffic; green strip approx. 1 m wide; only occasionally overgrown with grasses. Species appearance: crown close to the neighbouring tree, closely planted; columnar crown; a just-grown main shoot; many side shoots; flowers are just drying; some suckers just below the crown. Shoot death: none. Crown defoliation: none. Leaf damage: slightly wavy in the lower area; more wavy in the upper area. Bark: a few cuts with cracks. **VSt**: I.

UB10: Sycamore maple (*Acer pseudoplatanus*). Planting year: 1900. Location: Karl-Tauchnitz-Straße (centre), busy 3-lane street, high tram traffic, sealed sidewalk, very small tree slice, completely overgrown with ground cover, closely embedded between two buildings. Species appearance: tall tree with a rounded to oval, rather misshapen crown, heavily branched, strong, sloping trunk, strong formation of riders halfway up the trunk. Shoot death: some larger branches have died. Crown defoliation: yes, slight deficits in the lower area and on the outer edge. Leaf damage: leaves withered/brown at the edges (necrosis), size differences in some cases very large. Bark: light areas where the outermost layer is gone. **VSt**: II.

UB60: plane tree (*Platanus x acerifolia*). Planting year: 1920. Location: Wilhelm-Sammet-Straße, quiet side street, hardly any traffic, high degree of sealing with mostly cobblestones which directly adjoins the base of the trunk. Species appearance: very tall and spreading crown with a round shape, one main shoot with strong side shoots, many fruits developed, some rather stunted, some riding on the branches. Shoot death: several smaller ones. Crown defoliation: no leaves near the main shoot, the crown is only developed in

(*continued on next column*)

(*continued*)

the outer areas. Leaf damage: increasingly dried, slightly wavy leaves. Bark: old, isolated bulges, a large bulge, otherwise smooth bark, the base of the trunk is already growing beyond the edge of the curb. **VSt**: II.

UB38: Common ash (*Fraxinus excelsior*). Planting year: 1950. Location: in a field (outskirts); no sealing in the vicinity, adjoins the sports field and grain fields, gravel road. Species appearance: several main trunks as well as strong side shoots, crown with leaves on one side, close planting with other trees, no fruit formation, rider rate on branches and in the crown. Shoot death: very high proportion of dead wood at approx. 35%, smaller and larger branches affected. Crown thinning: one half extremely thinned and the upper part of the crown with deficits. Leaf damage: some of them are already very curled or dried, as well as a few spots (necroses) and holes. Bark: lichen growth, several older cuts with overburden and flaked off on dead branches. **VSt**: III.

UB124: Hungarian oak (*Quercus frainetto*). Planting year: 2019. Location: Kochstraße (Südvorstadt), small tree slice approx. 1×2 m, high degree of sealing, protection of young plants, protective coating of bark available, undergrowth with perennials. Species appearance: main shoot cut off, stunted crown, columnar to conical, tree dies, Shoot death: yes. Crown defoliation: yes. Leaf damage: yes, all dried or already fallen off. Bark: no visible damage or abnormalities. **VSt**: III.

UB132: Norway maple (*Acer platanoides*). Planting year: 2011. Location: Schönefelder Strasse (Eutzitsch); cobblestone pavement, narrow green strip between the pedestrian path and the street, minimal traffic and pedestrian traffic, moderate sealing density, adjacent to allotment gardens. Species appearance: completely leafless, bark protection coating still evenly present; dead (total failure). Shoot death: yes, complete. Crown defoliation: yes. Leaf damage: yes, completely discarded. Bark: no abnormalities. **VSt**: IV.

Correlation analysis

To examine the direction of the relationship between the different variables in the damage model and the surrounding soil sealing, Spearman's nonparametric rank correlation analysis was applied. In comparison to Pearson's correlation coefficient, this analysis is more suitable since it can be used for ordinally scaled data (Held, 2010). The field sample data were (standing age) and ordinally scaled (total damage, vitality, and sealing) in nature. For the calculation of the rank correlation coefficient ***rSP***, the values of the data series were replaced by ranks using rank ties (Held, 2010). A binding of ranks means that the same values in a data series have the same rank (ibid.). For the rank of a value, the mean is calculated from the sum of all ranks with the same value. The rank correlation coefficient can have values between −1 and +1 (Held, 2010). The closer the value approaches +1 or −1, the stronger the positive (rising) or negative (falling) relationship is (Hilgers et al., 2019). The value 0 represents no connection (ibid.). Eq. (1) introduces the calculation of the rank correlation coefficient ***rSP***:

$$r_{SP} = \frac{n^3 - n - \frac{1}{2}T_x - \frac{1}{2}T_y - 6Q}{\sqrt{(n^3 - n - T_x)(n^3 - n - T_y)}} \tag{1}$$

where $n = 137$ is the number of examined trees (Bradburn, 2020); Q is the sum of squares of the rank differences d^2; and T (x; y) is the sum of the ranks of the examined variables. Based on the calculation of the p value, the error probability or statistical significance of the relationship between the examined variables represented by ***rSP*** was calculated (Sedgwick, 2014). A value below the critical limit of 0.05 (probability of error <5%) is usually referred to as a statistically significant result (ibid.). The lowest value receives the lowest rank (Held, 2010). The corresponding rank mean values (*TSt*, *TGs*) were inserted into Eq. (1). *TSt* is the sum of the ranks of the standing age, and *TGs* is the sum of the ranks of the total damage.

Results

In the following section, the results of the mapping will be presented. In doing so, all field data and visual interpretation have been summarized and plotted; the original data sheets are available in the supplement of this paper (Appendix I). The damages identified as well as the state of health of the examined individual street trees are given in categorical data, 0 or 1 for the damage characteristics and in levels 1 to 4 [*Vst* I - IV] for the tree vitality state and, finally, levels 0 to 3 for the degree of soil sealing. The total number of mapped street trees per species, vitality level and their percentage are given in Table 3.

Fig. 4 presents a map of the sampled street trees along a periurban-urban gradient within the city of Leipzig, including the vitality levels of each mapped tree, using a green (no damage) to red (dead tree) colour code, which was introduced in the methods section.

Fig. 5 shows the vitality levels of the mapped street trees per genus/species. The distributions are presented in stacked column charts to enable a direct comparison between the species. *Platanus* and *Tilia* were recorded as healthy in more than 20 of the individual trees examined (*Vst* I), which was between 70 and 80% of all trees mapped. Compared to *Tilia, Quercus* (38.9%), *Fraxinus* (36.8%), *Acer* (30%) and *Aesculus* (25%) show lower proportions of individual trees in good health; in some cases, significantly less than 40% of the trees examined were in good health. For *Acer* and *Aesculus*, the proportion of damaged street trees classified as vitality level II–already damaged–accounted for more than half (*Acer*: 55%, *Aesculus*: 56.3%) of the trees and exceeded the number of trees under study in *Vst* I. For *Fraxinus* (36.8%) and *Quercus* (44.4%), approximately 1/3 of the street trees mapped were classified as vitality level *Vst* II. Both *Platanus* and *Tilia* (25.8% and 24.2%) had smaller proportions of individuals in this second vitality category.

The largest percentage of more severely damaged individuals assigned to vitality class *Vst* III occurred for *Fraxinus* at 26.4%, followed by *Aesculus* at 18.7%. In vitality class *Vst* IV, a total of two completely dead individuals were documented, one *Quercus* and one *Acer* (Table 3). Both were young trees, planted from 2018 to 2011. Premature death (total failure) in the first few years after planting–as in these two cases–can be triggered by water and nutrient deficiencies, soil compaction or root and trunk damage but can also result from improper planting or crown pruning (Hoffmann, 2008). Böll et al. (2018) note poor-quality nursery trees and traffic accidents as potential causes of total failures in the Urban Green Project 2021. However, the exact causes cannot usually be clearly identified (Nowak et al., 1990). In this study, for the two dead young trees in the sample, no major external damage to either trunk or root area could be found. The neighbouring young trees of the two dead ones were in better condition but also showed symptoms of heat and drought stress, such as wilted leaves and bent sprouts. A lack of water could be one reason for the dead young plantings if there was high competition for resources due to a high tree density or due to their proximity to mature trees (Fig. 5). An in-depth study should be considered here to identify the specific causes of such premature street tree death.

Damage traits per species

Fig. 6 displays both the number and share of types of street tree damage per genus that were documented during the field study. For this purpose, the number of mapped types of damage listed in Table A1 in the Appendix (1 = damage) was determined for each damage characteristic. Due to the number of mapped damage traits introduced in the methods section, an individual street tree could have 0 to 3 damage traits at the same time. Leaf damage was most frequently documented trait for all species, and the damage traits shoot death and crown defoliation (canopy dedensification) were found less frequently but apparent. Except for *Fraxinus*, all other species had shoot death occur more frequently than crown defoliation (see again Fig. 6).

Leaf damage was documented a total of 19 times for *Acer*. The damage characteristics shoot death (10) and crown defoliation (9) occurred less frequently. With a sample size of 20 individuals and a total of 38 documented damage traits, each species reported an average of ~1.9 damage traits. For *Aesculus*, 36 harmful traits were found in a total of 16 individuals. The average for *Aesculus* was ~2.25 damage traits with leaf damage documented 17 times, shoot death documented 11 times and crown defoliation documented 8 times. The 38 damage traits found for *Fraxinus* were distributed amongst 19 individuals, with an average of two damage traits per tree. Leaf damage was found 15 times, crown defoliation was found 12 times, and shoot death was found 11 times. *Platanus* had the highest number of individual damages traits, with 41 damage traits observed in a total of 31 individuals. Due to the larger sample of *Platanus*, each tree examined showed an average of

Table 3
Total number of mapped street trees per vitality category per species and their percentage

	Acer	*Aesculus*	*Fraxinus*	*Platanus*	*Quercus*	*Tilia*
V_{St} I	6 (30%)	4 (25%)	7 (36,8%)	22 (80%)	7 (38,9%)	23 (69,7%)
V_{St} II	11 (55%)	9 (56,3%)	7 (36,8%)	8 (25,8%)	8 (44,4%)	8 (24,2%)
V_{St} III	2 (10%)	3 (18,7%)	5 (26,4%)	1 (3,2%)	2 (11,1%)	2 (6,1%)
V_{St} IV	1 (5%)	0 (0%)	0 (0%)	0 (0%)	1 (5,6%)	0 (0%)

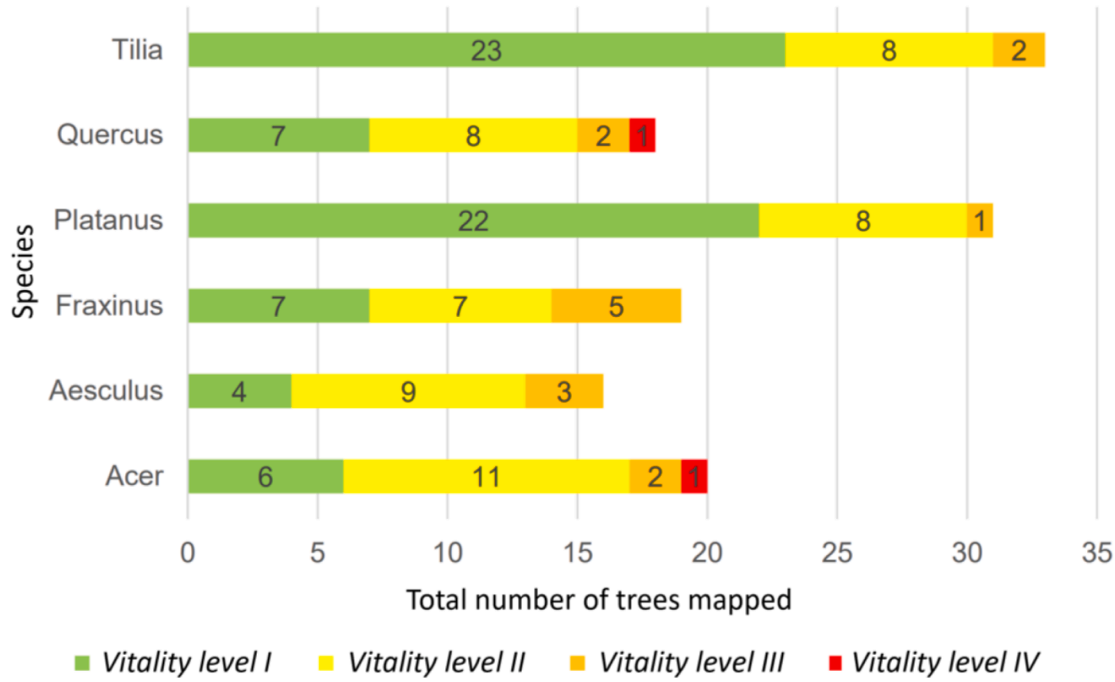


Fig. 5. Vitality levels of the mapped street trees per species: Acer and Quercus show the lowest vitality, and Tilia and Platanus show the highest vitality (per number and share).

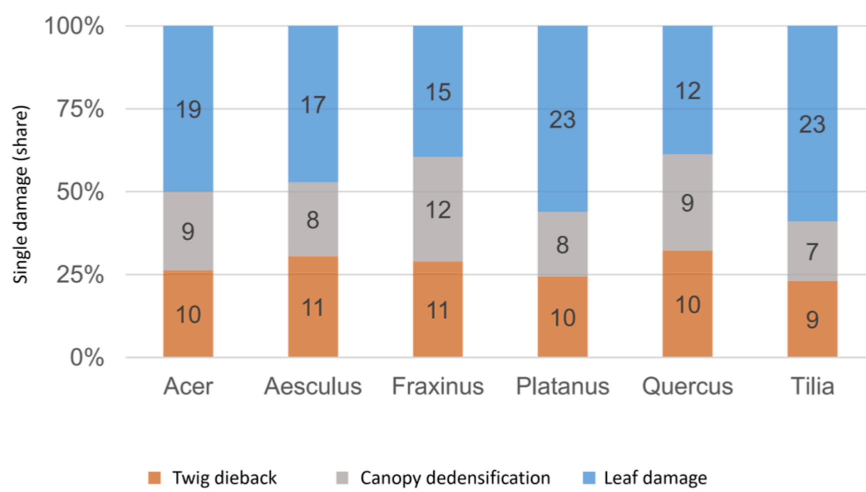


Fig. 6. Documented damage traits of the mapped tree species (total number and percent).

~1.3 damage traits, with most frequently observed trait being blade damage (23). Features of shoot death and crown defoliation were found 10 and 8 times, respectively. For *Quercus*, a total of 31 damage traits were found for 18 individual trees, with an average of ~1.7 damage traits per tree. Leaf damage was the most common feature for *Quercus* for all 12 observations. Shoot death was documented 10 times, and crown defoliation was documented 9 times. For *Tilia*, a total of 39 damage traits were found in the 33 street trees examined. This result means that each tree showed an average of ~1.2 damage traits per tree. Most damage was classified into the leaf damage category (23). The damage traits shoot death (9) and crown defoliation (7) were documented less often.

Comparing all six street tree species, on average, *Tilia* had the fewest damage traits per individual tree, and *Aesculus* had the most damage traits per tree. The second to fourth positions occurred in the following order of increasing average value: *Platanus, Quercus*, and *Fraxinus* and *Acer* with the same value. More specifically, *Aesculus, Fraxinus* and *Acer* showed an increased susceptibility to drought stress and heat stress, as documented by the high number of documented damage traits.

Damage traits per age class

The next step was the evaluation of the distribution of the examined damage traits for the trees by the age classes introduced in the methods section (Fig. 7). A plot was used to compare the distribution of damage within a genus with the respective age classes. For *Acer, Aesculus, Quercus* and *Tilia*, the most damage occurred in the middle-aged trees. For *Fraxinus* and *Platanus*, the middle-aged trees experienced the least amount of damage, while the highest number of damage traits was assigned to the category of old plantings in both species. In the young trees, *Aesculus, Fraxinus* and *Tilia* showed the fewest damage traits. Old individuals of *Acer* and *Quercus* exhibited the lowest number of damage traits.

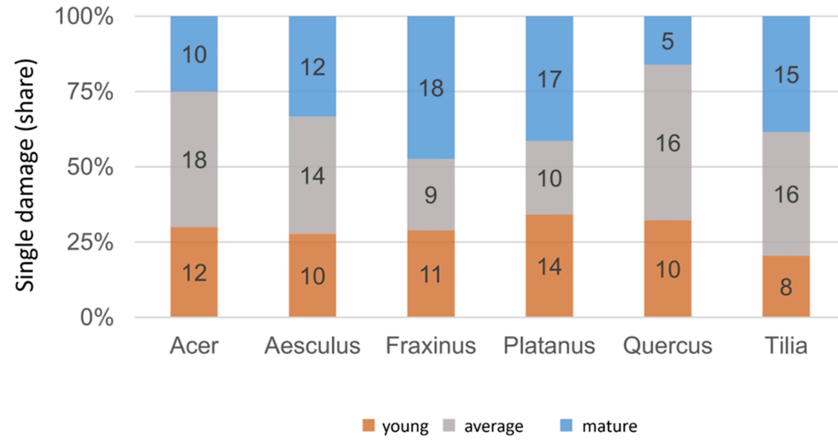


Fig. 7. Documented damage traits of the mapped trees by age class (total number and percent): young, average age and mature trees.

Correlation between damage trait, age class and soil sealing

To determine a possible relationship between tree age and the number of total damage traits per street tree (species), the mean ranks were calculated as introduced in the methods section and resulted in 0.34 for ***rSP***. Thus, a moderate positive relationship between the damage traits was observed stated ($p = 0.00003 < 0.001$; cumulative Student's t-test = 4.169; degrees of freedom 135). Increased tree age weakly positively correlated with a high number of total damage traits. Old trees tend to have more damage than young trees. To confirm this as a statistical relationship, the assumption of a positive relationship between age class and vitality level was tested. The correlation coefficient ***rSP*** between age class and vitality (*Vst*) was calculated in the same way to determine the relationship between the ranks of the two variables.

As stated in the Introduction at the beginning of this paper, tree resistance decreases with age, and tree damage conversely tends to increase. A one-sided alternative hypothesis *H*1.1 was proposed that assumed that young trees are in better health due to the increased maintenance effort in the first few years after planting and a higher capacity to adapt to changing environmental influences and that overall, these trees have a lower level of damage than middle-aged and mature street trees. In addition, *TSt* being the sum of the ranks of the values from the variable 'age class' and *TV* corresponding to the sum of all ranks of the variable 'vitality', a Spearman correlation coefficient ***rSP*** of 0.24 showed a weak positive correlation between the two variables (***rSP*** <0.3> 0). A high rank for the variable 'age class' (equal to mature tree) correlated higher with a high rank for the variable of 'vitality' (poor health state; $p = 0.004 < 0.005$; cumulative Student's t-test = 2.714; degree of freedom 135, which for the observed relationship indicates a high statistical significance). The null hypothesis *H*0\0.1–all street trees are in poor health under urban heat and drought island conditions regardless of the age class–could not be confirmed. Despite the low strength of the relationship, the relationship between tree age and mapped vitality level was significant. Further studies with a larger sample should be carried out to verify the results of this study (Fig. 8).

Fig. 8 shows the number of trees classified into vitality levels and age classes. For the young trees, a good health state was documented for the vast majority of the mapped trees (*Vst I* = 32). *Vst* II-IV levels were assigned to significantly fewer young trees (*Vst* II = 12, *Vst* III = 2, *Vst* IV = 2), meaning that most were still in a moderate condition, and only two trees were each classified as damaged to severely damaged or dead. Average-age trees up to 50 years old and mature trees above 50 years old had no individuals categorized as *Vst* IV, whereas the number of moderately damaged and damaged trees (*Vst* II and III = 26 for medium-

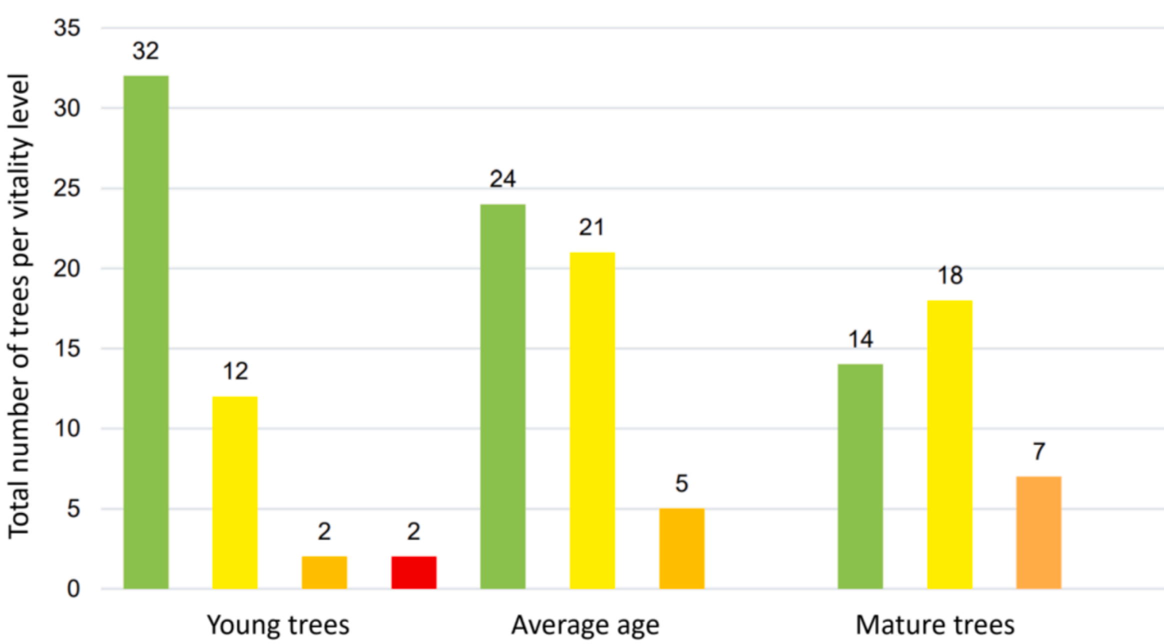


Fig. 8. Documented vitality levels of the mapped tree age classes (total number and percent): young, average-age and mature trees.

old age classes, *Vst* II and III = 25 for mature trees) was significantly higher than that of young trees. For the old trees, the occurrence of the highest vitality level *Vst* I was lowest (14), and the number of trees in *Vst* II and III was overall higher than that in *Vst* I (25>14). Most of the mapped old trees were already in a poor health state. The sample further suggests a trend of a decreasing health with increasing age.

Another correlation analysis was conducted to confirm the relationship between soil sealing and street tree vitality. According to the assumption of the alternative hypothesis *H*1.2, street trees in heavily sealed, highly urbanized locations are in poorer health and show more symptoms of damage than street trees in locations with lower sealing rates, such as in peri-urban surroundings (Dickhaut et al., 2019; Mullaney et al., 2015). With a correlation coefficient *rSP* of 0.09 but with an error probability of >10% (p 0.134), it was not statistically confirmed that poor tree health could be explained by a high degree of sealing. For a more meaningful result, further factors must be included in addition to increasing the size of the tree sample.

Discussion and conclusions

This study shows that the damaged trees differed in terms of both tree age class and tree species, which is in line with the results of other pilot studies and reviews on climate-change-induced tree damage (Matyssek et al., 2012; Allen et al., 2010; Hartmann et al., 2018). For Leipzig, damage occurred at a very specific level for the studied age classes of the street tree species. We show that in four out of the six examined dominant tree species, there were trees with an increased risk of harm. The field study clarified that *A. hippocastanum* or other *Acer* species are already exhibiting increased levels of various damage types. In addition, an above-average proportion of these old trees are individual trees in very poor health, despite *Acer* species being shown to have a wide range of tolerance to water deficits in a Swedish study for urban trees (Sjöman et al., 2015). *Fraxinus* and *Quercus* also had a high number of damaged populations within the studied sample, particularly old trees over 50 years old. In this study, *Tilia* and *Platanus* had a high proportion of individuals that were in good health, showing a very limited amount of damage. As already stated in the introduction, both of these tree species are reported to be well adapted to dryer and water-stressed urban climates and thus cope better with the examined stress factors (Roloff et al., 2008; GALK, 2012). It was also confirmed that young trees are more likely to be in good health than older trees. Mature trees were classified as particularly at risk for damage from heat and drought, with *Aesculus* and *Quercus* being amongst the most endangered. A study by Baggett (2019) in North America also found that *Quercus* and *Aesculus* face severe threats from hotter and drier climate conditions and projects that these species will soon be lost from the urban tree canopy of cities that continue to experience intense heat effects.

To detect street tree damage at an early stage–meaning earlier than the visible damage mapped in this study–tree shoots, crown structures and patterns need to be continuously monitored at a young age and over a longer period to obtain reliable and long-term information on growth behaviour and the changing state of health (Becker, 1999). Many harmful processes start long before the damage appears in the tree, so deficits in the crown or canopy can often be traced back to damage in the root area and thus have a belowground cause that usually only becomes visible in the crown structure after a delay (ibid.). Urban trees can also accumulate stress over a longer period of time before this stress becomes visible–or detectable using the field method applied in this paper (ibid.; Roloff et al., 2008). For such longer-term monitoring, satellite, hyperspectral and aerial photography of the earth can be helpful when applied to recent literature to identify proper spectral signals for early damage to street trees (Wellmann et al., 2020).

Another conclusion from this pilot study is that the different causes of damage could be differentiated through a closer examination and analysis of the various components of a tree, such as leaves, trunk, branches, or bark. An expansion of the sample size for each genus and the examined damage characteristics would increase the value of the results and reduce the risk of potentially misinterpreting the subjective observations. However, the results of this specific street tree study provides important conclusions about the susceptibility of the examined species to a combination of heat and drought stress resulting from three extremely hot and dry seasons. Moreover, the data obtained can serve as a foundational and ground-truthing data that can be compared with data from potential long-term monitoring data on the health of the entire street tree population of Leipzig. It is impossible due to the limited sample of this study to draw long-term conclusions, but future studies should aim to determine which tree species have an increased failure rate. In addition to drought, other issues, such as improper planting, unsuitable soil, unfavourable conditions, or lack of management, can results in the failure of new plantings or the death of young trees just a few years after planting, (Wellmann et al., 2018). Should these types of observations be obtained for certain species, it must be determined whether the specific species are still suitable for the climatic and site-specific urban conditions in Central Europe. In addition, species that are susceptible to heat should be monitored carefully and cared for to increase life expectancy and prevent premature felling. However, in the future, these species should be replaced by urban plantings, which, in addition to the properties considered here concerning drought tolerance and heat tolerance, also should have frost tolerance, tolerance to air pollution, a high ability to resist compacted soil, and resistance to pests and diseases (Mullaney et al., 2015).

Due to the limited number of variables examined in this pilot study and the small sample size, the results of the study are subject to some degree of uncertainty. The mere visual inspection of a tree cannot provide information on processes that are caused by heat and drought stress but not externally directly visible or not recognizable without further study. The collected field data reflect the state of health and the visible distribution of damage as a pilot study. Notably, the sample sizes and the age categories of the species in this study were different sizes. To a limited extent, only three significant damage characteristics–leaf damage, shoot death, and crown defoliation–were selected as indicators for determining the condition of the objects to be examined and the evaluation. Additional characteristics that could provide further information about tree health–height, trunk circumference, growth rate, time of leaf shoot, leaf shedding, photosynthesis capacity, transpiration rate or water content of the leaves–were not collected here due to a lack of resources (Böll et al., 2018).

An increase in the diversity of the street tree population as a response to urban heat and drought will increase overall tree resistance to external influences and inhibit the spread of diseases and parasites. Therefore, the biodiversity of the tree population in cities should be increased through further plantings, and new suitable species should urgently be planted, as reported in international literature (Roloff et al., 2008; GALK, 2009; Manes et al., 2012). The findings of this mapping study for the city of Leipzig and the conclusions drawn from them offer valuable reference points for both the maintenance of existing tree species and the selection of new more sustainable tree species for the urban area that provide important ecosystem services (Rötzer et al., 2019). Further in-depth research is still required to identify specific, regionally adapted tree species for use in urban planning.

Declaration of Competing Interests

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was carried out, partly, as part of the EU Horizon 2020 project CONNECTING Nature – COproductioN with NaturE for City

Transitioning, Innovation and Governance (Project Number: 730222) and the CLEARING HOUSE project which has received funding from the European H2020 Research and Innovation programme under the Grant Agreement n° 821242. The content of this document reflects only the author's view. The European Commission is not responsible for any use that may be made of the information it contains.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2022.100252.

References

Allen, C.D., et al., 2010a. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259, 660–684, 2010.
adelphi/PRC/EURAC, 2015. Vulnerabilität Deutschlands gegenüber Dem Klimawandel. Climate Change, 24/2015. Dessau-Roßlau, Umweltbundesamt, Hrsg.).
Alavipanah, S., Schreyer, J., Haase, D., Lakes, T., Qureshi, S., 2018. The effect of multi-dimensional indicators on urban thermal conditions: an example from the arid city of Yazd, Iran. J. Cleaner Prod. 177, 115–123. https://doi.org/10.1016/j.jclepro.2017.12.187.
Allen, C.D., Macalady, A., Chenchouni, H., Bachelet, D., Mcdowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E., 2010b. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259 (4), 660–684. Elsevier2010.
Baggett, A. (2019) Combatting the urban heat island effect: what trees are suitable for Atlanta's current and future climate? School of City and Regional Planning Applied Research and Option Papers [241], http://hdl.handle.net/1853/61322.
Beck, P., Caudullo, G., Tinner, W., de Rigo, D, 2016. Fraxinus excelsior in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (Eds.), European Atlas of Forest Tree Species. Luxembourg, pp. 98–99.
Becker, A., 1999. Baumpflege - Unter besonderer Berücksichtigung baumbiologischer Zusammenhänge. Diplomica Vertrag GmbH.
Benning, J. (2021). Platane. Baumportal.de: https://www.baumportal.de/Platane.htm. Accessed: 22.02.2021.
Biercamp, N., Hirschfeld, J., Mohaupt, F., Müller, R., Riousset, P., Spreter, R., Welling, M., Wissel, S. and Witzel, M. (2018). Stadtgrün wertschätzen - Grünflächenmanagement im Kontext von Klimawandel und Biodiversität. Synthesebericht zum Modul I des Projekts STADTGRÜN.
Böll, S., Schönfeld, P., Körber, K., Herrmann, J.V., 2014. Stadtbäume im Stress - Projekt "Stadtgrün 2021" untersucht Stadtbäume im Zeichen des Klimawandels. LWG aktuell 4–8.
Bradburn, S. (2020). How To Perform A Spearman's Rank Correlation Test In Excel. https://toptipbio.com/spearman-correlation-excel/. Accessed: 04.03.2021.
Brune, M., 2016. Urban Trees Under Climate change. Potential impacts of Dry Spells and Heat Waves in Three German regions in the 2050s. Climate Service Centre Germany, Hamburg.
Bundesamt für Naturschutz (BfN), 2020. Wälder Im Klimawandel: Steigerung von Anpassungsfähigkeit und Resilienz durch Mehr Vielfalt und Heterogenität. Bonn - Bad Godesberg.
Caudullo, G., Houston Durrant, T., 2016. Fraxinus angustifolia in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (Eds.), European Atlas of Forest Tree Species. Luxembourg: Publ. Off. EU. S. 97.
Deutscher Wetterdienst (DWD), 2021. Klima aktuell Sachsen. Leipzig (Flugh. https://www.dwd.de/DE/wetter/wetterundklima_vorort/sachsen/leipzig/_node.html. Accessed: 22.03.2021.
Dickhaut, W., Doobe, G., Eschenbach, A., Fellmer, M., Gerstner, J., Gröngröft, A., Jensen, K., Lauer, J., Reisdorff, C., Saner, A., Titel, S., Wagner, A., Winkelmann, A., 2019. Entwicklungskonzept Stadtbäume. Anpassungsstrategien an Sich Verändernde Urbane Und Klimatische Rahmenbedingungen. Universität Hamburg (Hrsg.
Dobbertin, M., Hug, C., Waldner, P., 2009. Kronenverlichtung, Sterberaten und Waldwachstum in Langzeitstudien–Welche Indikatoren beschreiben den Waldzustand am besten? Forum für Wissen 7–20, 2009.
Dobrowolska, D., Hein, S., Oosterbaan, A., Wagner, S., Clark, J., Skovsgaard, J.P., 2011. A review of European ash (Fraxinus excelsior L.): implications for silviculture. Forestry 84 (2), 133–148.
Dörken, M., Steinecke, H., 2017. Tilia cordata – Winter-Linde (Malvaceae), Baum des Jahres 2016, und weitere Lime tree. Jahrb. Bochumer Bot. Ver. 8, 306–318.
Duthweiler, S., Pauleit, S., Rötzer, T., Moser, A., Rahman, M., Stratopoulus, L., Zölch, T., 2017. Untersuchungen zur Trockenheitsverträglichkeit von Stadtbäumen. Jahrbuch der Baumpflege, 21. Jhg. 137–154.
Eaton, E., Caudullo, G., Oliveira, S., de Rigo, D, 2016. Quercus robur and Quercus petraea in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz, J., de Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (Eds.), European Atlas of Forest Tree Species. Publ. Off. EU, Luxembourg, pp. 160–163. S.
Egerer, Monika, Haase, Dagmar, McPhearson, Timon, Frantzeskaki, Niki, Andersson, Erik, Nagendra, Harini, Ossola, Alessandro, 2021. Urban change as an untapped opportunity for climate adaptation. NPJ Urban Sustain. 1, 22. https://doi.org/10.1038/s42949-021-00024-y.
European Environment Agency (EEA), 2017. Climate change, Impacts and Vulnerability in Europe 2016. An indicator-Based Approach. Publ. Off. EU, Luxembourg.
GALK (Arbeitskreis Stadtbäume), 2002. Empfehlungen Zur Beurteilung von Bäumen in Der Stadt. https://galk.de/arbeitskreise/stadtbaeume/themenuebersicht/empfehlungenzur-beurteilung-von-baeumen-in-der-stadt. Accessed: 06.02.2021.
GALK. (Arbeitskreis Stadtbäume) (2009). Positionspapier Stadtbäume und Klimawandel. https://galk.de/component/jdownloads/send/3-positionspapiere/37-positionspapier-klimawandel-und-stadtbaeume. Accessed: 04.02.2021.
GALK. (2012). GALK Straßenbaumliste. https://www.galk.de/arbeitskreise/stadtbaeume/themenuebersicht/strassenbaumliste/galk-strassenbaumliste. Accessed: 05.02.2021.
Giller, S., Bräuning, A., Roloff, A., 2014. Dendrochronological analysis of urban trees: climatic response and impact of drought on frequently used tree species. Trees 28, 1079–1093.
Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T., Sperry, J.S., McDowell, N.G., 2020. Plant responses to rising vapor pressure. New Phytol. 226, 1550–1566.
Use of Forest Tree Species Under Climate Change Grundmann, B.M., Roloff, A., Feldmann, F., Alford, D.V., Furk, C., 2009. Crop Plant Resistance to Biotic and Abiotic Factors. Deutsche Phytomedizinische Gesellschaft (Hrsg, Braunschweig, pp. 53–65. S.
Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., Gomez-Baggethun, E., Gren, A., Hamstead, Z., Hansen, R., Kabisch, N., Kremer, P., Langemeyer, J., Lorance Rall, E., McPhearson, T., Pauleit, S., Qureshi, S., Schwarz, N., Voigt, A., Wurster, D., Elmqvist, T., 2014. A quantitative review of urban ecosystem services assessment: concepts, models and implementation. Ambio 43 (4), 413–433.
Hartmann, H., et al., 2018. Research frontiers for improving our understanding of drought-induced tree and forest mortality. New Phytol. 218, 15–28.
Held, U., 2010. Tücken von Korrelationen: die Korrelationskoeffizienten von Pearson und Spearman. Swiss Med. Forum 10 (38), 652–653.
Hilgers, R.-D., Heussen, N., Stanzel, S., 2019. Korrelationskoeffizient nach Spearman. In: Gressner, A.M., Arndt, T.(Hrsg.), (Eds.), Lexikon Der Medizinischen Laboratoriumsdiagnostik. Springer, Berlin, Heidelberg, p. 1390. S.
Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K.L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S.I., Thomas, A., Warren, R. and Zhou, G. (2018). Impacts of 1.5ºC Global Warming on Natural and Human Systems. In Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T., Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press.
Hoffmann, L. (2008). Baumschadensdiagnose. https://www.astwerk.de/fileadmin/baumschadensdiagnose.pdf. Accessed: 08.02.2021.
Ishii, H.T., Ford, E.D., Kennedy, M.C., 2007. Physiological and ecological implications of adaptive reiteration as a mechanism for crown maintenance and longevity. Tree Physiol. 3, 455–462.
Lin, Brenda, Ossola, Alessandro, Ripple, William, Alberti, Marina, Andersson, Erik, Bai, Xuemei, Dobbs, Cynnamon, Elmqvist, Thomas, Evans, Karl L, Frantzeskaki, Niki, Fuller, Richard, Gaston, Kevin J., Haase, Dagmar, Jim, C.Y., Konijnendijk, Cecil, Nagendra, Harini, Niemela, Jari, McPhearson, Timon, Moomaw, William R, Parnell, Susan, Pataki, Diane, Yok Tan, Puay, 2021. Cities and the "new climate normal": ways forward to address the growing climate challenge. The Lancet Planetary Health.
Manes, F., Incerti, G., Salvatori, E., Vitale, M., Ricotta, C., Costanza, R., 2012. Urban ecosystem services: tree diversity and stability of tropospheric ozone removal. Ecological Applications 22 (1), 349–360.
Marx, A. (2021). Dürremonitor Deutschland. https://www.ufz.de/index.php?de=37937. Accessed: 10.02.2021.
Matyssek, R., Schnyder, H., Oßwald, W., Ernst, D., Munch, J.C., Pretzsch, H., 2012. Growth and defence in plants. Ecol. Studies 220.
Mauri, A., Enescu, C.M., Houston Durrant, T., de Rigo, D., Caudullo, G, 2016. Quercus frainetto in Europe: distribution, habitat, usage and threats. In: SanMiguel-Ayanz, J., de Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (Eds.), European Atlas of Forest Tree Species. Publ. Office EU, Luxembourg, pp. 150–151. S.
McDonald, Robert, Mansur, Andressa V, Ascensão, Fernando, Colbert, M'Lisa, Crossman, Katie, Elmqvist, Thomas, Gonzalez, Andrew, Güneralp, Burak, Haase, Dagmar, Hamann, Maike, Hillel, Oliver, Huang, Kangning, Kant, Belinda, Maddox, David, Pacheco, Andrea, Pereira, Henrique, Seto, Karen, Simkin, Rohan, Walsh, Brenna, Ziter, Carly, 2019. The growing impacts of cities on biodiversity. Research gaps limit global decision-making. Nat. Sustain. https://doi.org/10.1038/s41893-019-0436-6.
McPhearson, T., Karki, M., Herzog, C., Santiago Fink, H., Abbadie, L., Kremer, P., Clark, C.M., Palmer, M.I., Perini, K., 2018. Urban ecosystems and biodiversity. In: Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S., Ali Ibrahim, S. (Eds.), Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network. Cambridge University Press, New York, pp. 257–318. S.
Moser, A., Rötzer, T., Pauleit, S., Pretzsch, H., 2015. Structure and ecosystem services of small-leaves lime (Tilia cordata Mill.) and black locust (Robinia pseudoacacia L.) in urban environments. Urban Forest. Urban Greening 14, 1110–1121.

Mullaney, J., Lucke, T., Trueman, S.J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landsc. Urban Plan. 134, 157–166.
Müller, U., 1999. Zur räumlichen Niederschlagsverteilung in der Stadt Leipzig. Wissenschaftliche Mitteilungen des Leipziger Instituts für Meteorologie 12, 91–97.
Nowak, D.J., McBride, J.R., Beatty, R.A., 1990. Newly planted street tree growth and mortality. J. Arbboricult. 16 (5), 124–129.
Nowotny, G., 2013. Stadtbäume in Salzburg (Österreich) 1983-2010. Ergebnisse langjähriger Untersuchungen zu Bestandsveränderungen, Vitalität und Wuchsbedingungen. CONTUREC 5, 67–84.
Pretzsch, H., Biber, P., Uhl, E., Dahlhaus, J., Schütze, G., Perkins, D., Rötzer, T., Caldentey, J., Koike, T., van Con, T., Chavanne, A., du Toit, B., Foster, K., Lefer, B., 2017. Climate change accelerates growth of urban trees in metropolises worldwide. Sci. Rep. 7, 15403.
Radoglou, K., Dobrowolska, D., Spyroglou, G., Nicolescu, V.N., 2008. A review on the ecology and silviculture of limes (Tilia cordata Mill., Tilia platyphyllos Scop. and Tilia tomentosa Moench. Europe. COST Office 29.
Roloff, A., Gillner, S., Bonn, S., 2008. Gehölzartenwahl im urbanen Raum unter dem Aspekt des Klimawandels. Sonderheft Grün ist Leben 30–42.
Rötzer, T., Rahman, M.A., Moser-Reischl, A., Pauleit, S., Pretzsch, H., 2019. Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions. Sci. Total Environ. 676, 651–664. https://doi.org/10.1016/j.scitotenv.2019.04.235.
Salmond, J.A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., Dirks, K.N., Heaviside, C., Lim, S., Macintyre, H., McInnes, R.N., Wheeler, B.W., 2016. Health and climate related ecosystem services provided by street trees in the urban environment. Environ. Health 15 (1), 96–111.
Schönfeld, P., 2016. Die Winterlinde und ihre Sorten als Stadtbaum. LWF Wissen 78, 45–52. SBayr. Landesanstalt für Wald und Forstwirtschaft (LWF) (Hrsg.) Veitshöchheim.
Schönfeld, P., 2019. Klimabäume" - welche Arten können in Zukunft gepflanzt werden? LWG aktuell, 2019, Bayr. Landesanstalt für Weinbau und Gartenbau (LWG) (Hrsg.), Veitshöchheim.
Sedgwick, P., 2014. Spearman's rank correlation coefficient. BMJ 2014, 349.
Steinike, W., Schwab, U., 2010. Stadtklimauntersuchung Leipzig. Steinike and Streifender Umweltuntersuchungen GbR. Freiburg.
Thober, S., Marx, A., Boeing, F., 2018. Auswirkungen der globalen Erwärmung auf hydrologische und agrarische Dürren und Hochwasser in Deutschland. Ergebnisse aus dem Projekt HOKLIM: Hochaufgelöste Klimaindikatoren bei einer Erderwärmung von 1.5 Grad. Helmholtz-Zentrum für Umweltforschung GmbH – UFZ.
Von Döhren, P., Haase, D., 2015. Ecosystem disservices research: a review of the state of the art with a focus on cities. Ecol. Indic. 52, 490–497.
Wellmann, T., Lausch, Angela, Andersson, Erik, Knapp, Sonja, Cortinovis, Chiara, Jache, Jessica, Scheuer, Sebastian, Kremer, Peleg, Mascarenhas, André, Kraemer, Roland, Haase, Annegret, Schug, Franz, Dagmar, Haase, 2020. Remote sensing in urban planning: contributions towards ecologically sound policies? Landsc. Urban Plan. https://doi.org/10.1016/j.landurbplan.2020.103921.
Wellmann, T., Haase, D., Knapp, S., Salbach, C., Selsam, P., Lausch, A., 2018. Urban land use intensity assessment: the potential of spatio-temporal spectral traits with remote sensing. Ecol. Indic. 85, 190–203. https://doi.org/10.1016/j.ecolind.2017.10.029.