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Traits of trees for cooling urban heat islands: A meta-analysis

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ABSTRACT

A more detailed understanding of the micro-climatic thermal benefits of different urban tree species and the retrospective species characteristics is necessary to guide management decisions. In this review, we focused specifically on empirical data collected at ground level for below-canopy surface temperature (ST) and transpiration cooling (AT), using a meta-analysis method. Tree canopy density was clearly identified as the most influential driver of different mechanisms of cooling benefits. Secondly, climate of the cities where the trees were grown showed significant impacts on cooling potentials: trees grown in Oceanic and Continental climates showed a higher cooling potential compared to trees grown in Mediterranean climate for AT and sub-tropical climate for ST. Thirdly, tree growth in size and ground surface cover showed significant impact. ST decreases almost linearly with the increase of canopy density; however, the rate is significantly lower over transpiring grass surfaces. Transpiration of trees planted over grass was ten times higher (4.15 g m^{-2} min^{-1}) compared to a tree planted in paved cut-out pits (0.44 g m^{-2} min^{-1}). Moreover, diffuse porous wood anatomy and trees originating from temperate and resource-rich forests showed better cooling potentials. Among the leaf traits, dark green leaves, < 0.15 mm of thickness showed higher AT and ST benefit. The review pointed out the lack of standardized study protocols in determining tree cooling benefits and empirical data, particularly at tropical and sub-tropical climate. Finally, the study suggested some recommendations for plantings that optimize the cooling benefits from urban greenspaces.

1. Introduction

The effects of the urban heat island (UHI) [1] have already been intensified with ongoing climate change [2]. As replacing vegetated surfaces by artificial structures is a major cause of UHI and thermal discomfort in open spaces [3], adding more vegetation seems to be the most important strategy for mitigating UHI [4] and improving thermal comfort in open spaces during the hot season [5]. For forested site, the *green soup hypothesis* [6] predicts that ecosystem productivity is mainly driven by vegetation biomass, suggesting that vegetation "quantity" is more important than vegetation "quality" [7]. Regarding the urban greenspaces, intensive research have been conducted over the last decade, to understand the impacts of urban greenspaces on urban microclimate, which resulted in a large number of single studies, specific case studies and an increasing amount of reviews [8–10]. At the same time, practical guidelines with information on the capacity of different tree species to regulate the micro-climate have been published [11]. However, a systematic and comprehensive review of the characteristics of different tree species and their potential of cooling the urban environment is still missing.

The cooling benefits of trees are caused by two main factors. Firstly, the canopies of trees provide shade, reducing the input of short wave radiation to ground level, by about 60–90% [12]. Consequently up to 40 °C surface temperature difference between shaded surfaces under the dense canopies of trees and sunny asphalt have been reported [13–15]. With differences in radiation intensity, and precipitation pattern and

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amount [16], surface cooling from trees can vary with climate. Still, surface cooling is comparatively easier to parameterize since structural characteristics such as plant functional type, growing size, wood anatomy, leaf colour, leaf shape, crown shape, leaf thickness and leaf area index (LAI) of trees are easy to measure [17]. However, leaf anatomical characteristics might also have an effect on reflection, transmission as well as retransmission on tree canopies [18]. Another important aspect is the surfaces over which the shading effect is investigated since the thermal properties of greenspaces or different kinds of paved surfaces such as asphalt, concrete and brick pavers are contrastingly different. Consequently, Rahman, Moser, Rötzer and Pauleit [14] showed a decrease in grass surface temperature of 3 °C with every unit of LAI but for asphalt, the reduction in surface temperature was about 6 °C. At the same time, a higher proportion of sealed surfaces can reduce the amount of water availability to the tree pits and it can increase the heat load and vice-versa influencing the tree transpiration.

Secondly, with evapotranspiration, trees reduce the amount of heat available to warm the air around them. Therefore, air temperatures can be significantly lower in the shade of trees than in the shade of buildings [19]. The direct impact of transpiration on reducing air temperature within or below the tree canopy varies between 1 °C and 8 °C [20,21]. Similar to the shading effect, dissipation of the heat load by transpiration cooling varies with climate [22,23], tree species [24,25] and environmental conditions [26]. Along with tree morphological characteristics, species differences owing to xylem anatomy, or water use efficiency, species can regulate their stomata and hence can have effect on boundary layer air temperature regulation [27,28].

Remote sensing using satellites can be an efficient tool to estimate the surface temperature of tree canopies and other land surface temperature. However, there is only a weak relationship between the leaf surface temperature and the convective heat of air in tree canopies, especially while comparing the benefits of different tree species. First, the outer boundary layers of the canopy always have a higher air temperature compared to the inner crown [21]. Second, leaf temperature is also dependent on anatomical, physical and physiological factors (such as leaf thickness, leaf hairiness, leaf colour, leaf shape, specific leaf area) [29]. Accordingly, researchers such as Knoerr and Gay [30], Leuzinger, Vogt and Korner [31] showed that small leaves have a lower boundary layer temperature up to 5 °C due to the faster loss of convective heat even if they are not transpiring faster.

Cooling effects of trees were quantified more frequently by measuring air temperatures directly within and outside parks or below and outside the tree canopy. This was the focus of meta-analyses by Bowler, Buyung-Ali, Knight and Pullin [8]; Zupancic, Westmacott and Bulthuis [9]; Motazedian and Leardini [32], even though, due to the efficient mixing of air [17], the difference in air temperature can hardly tell us the transpiration cooling potential. Considering the difficulties in investigating the boundary layer air-cooling due to transpiration, a more simple technique is to measure or model the water loss from trees. The total water loss can be multiplied by the latent heat of evaporation of water to calculate energy loss due to latent heat exchange and hence reduction in convection. Grimmond and Oke [33] reported an energy loss of 225 W m^{-2} from well-irrigated urban trees of different US cities. Long term transpiration cooling from individual urban trees of four most commonly planted species in Central Europe (*Tilia cordata*, *Robinia pseudoacacia*, *Platanus acerifolia* and *Aesculus hippocastanum*) were simulated by Rötzer, Rahman, Moser-Reischl, Pauleit and Pretzsch [34]. They reported that the cooling effect through transpiration ranged between 21,675 and 51,649 kWh $tree^{-1}$, which correspond to 59 and 75 W m^{-2}.

Several researchers have developed performance indices for urban trees based on the provision of ecosystem services [35] or considering the multi-functionality of street vegetation along with their resilience and dimensional traits [36]. However, a comprehensive overview of the tree species characteristics for micro-climatic thermal regulation and a meta-analysis of the dependencies between morphological and leaf traits, growth conditions, and cooling effect is missing so far. In this review, we focused specifically on empirical data collected at ground level for surface temperature and transpiration measurements. We reviewed studies that measured below-canopy surface temperature compared to sunny sites, water loss using different techniques and studies about the human thermal comfort with explicit information on geographic region, city of investigation, seasonality, tree species and tree parameters. Systematic review methods were used to provide a robust and clear framework for organizing relevant studies and synthesise their outputs. Afterwards meta-analysis was used to statistically combine the data on quantifying the cooling benefits based on prominent tree parameters. Finally, our review aimed to investigate the relative strength of the major determinant variables and their influence on the cooling potentials of different species for shading effect on surface cooling and transpiration air-cooling, and consequently on human thermal comfort. The review analysed the published studies to understand the effects of i. climate ii. tree morphological, leaf and xylem anatomical traits and iii. local growth conditions on tree cooling potentials. At the end, suggestions for decision-makers of the urban green, e.g., landscape planners, gardeners, and architects are provided.

2. Search and selection of studies

The overarching aim of the meta-analysis was to investigate the effects of tree characteristics (leaf features, growing size, wood anatomy, crown features and plant functional type) as well as the site climate, the surface of the growing site (sealed, grass) and the native growing habitat on the cooling capacity (shading, transpiration, human thermal comfort) of individual urban trees. To ensure the most unbiased results possible, this review included only the field studies following the screening rules set by Stewart [37]: i. tree's potential on below-canopy surface cooling, water loss and regulation of human thermal comfort measured for trees grown in urban growth conditions ii. clearly defined number, and location of urban trees as well as measured variables iii. sufficient site description and iv. effort to control confounding factors.

For searching relevant studies we used internet search engines and websites of environmental organizations, applying combinations of relevant keywords (such as shading, trees, transpiration, urban), and databases for leaf parameters and xylem anatomy. Inclusion criteria were met with studies that investigated the effect of single trees in urban areas in any geographic location that compared the shading benefit under the canopies with appropriate control sites and measured the water loss mainly using sap flow or porometric techniques. After checking the abstracts of all search results, a selection of 37 peer-reviewed papers were seen as relevant for the review. This selection was further reduced to 26 papers. We used authors' description for sites and looked at the Köppen–Geiger climate classification system [38], we extracted all the morphological data from the articles. For missing parameters on leaf characteristics, we used the TRY database (http://www.try-db.org) data, other online databases (https://www.vdberk.de/) and the database of the University of Florida (http://hort.ufl.edu/database/trees/trees_scientific.shtml). Wood anatomy information was taken from a database on wood anatomy (http://www.woodanatomy.ch) and from Alves and Angyalossy-Alfonso [39]. Additional tree characteristics such as original habitat and growing size classification were derived from Roloff and Bärtels [40]. Further data on leaf area, leaf thickness, specific leaf area (SLA) and leaf shape were added after studies of Hu, Dai and Sun [41], Abrams and Kubiske [42], Abrams, Kubiske and Mostoller [43], Carpenter and Smith [44], and Moser, Roetzer, Pauleit and Pretzsch [45].

Moreover, several of the studies investigated the influence of trees only on surface cooling whereas the others investigated transpirational cooling of trees. Some studies investigated the effects of parameters such as street canyon, sky view factor (SVF), proportion of built surfaces, planting design on the tree cooling effect. Therefore, these studies tend to overlap as researchers concurrently studied multiple parameters. We also considered these overlapping studies for relevant sections (i.e. one study might have been used for both shading and human thermal comfort) individually.

3. Analysis of studies

All selected studies (Table 1) were characterized (Table 2) and the available information as well as the extracted data was summarized (Table 3). From each study, we extracted information on methods, time of investigation, location, number of trees, morphological and leaf traits, growth conditions and consequent cooling potentials manually. Moreover, we used the freely available software Engauge Digitizer (Version 10.4) that accepts image files containing graphs and recovers the data points from those graphs, for instance, the trees grown on different growth conditions (grass lawns, cut-out pits) and their cooling potentials. The results with respect to the potential cooling benefits were accumulated in terms of the difference of surface temperature ΔST (sunny – shaded surface) and per unit leaf area water loss (E_L). The extracted data sets were subjected to meta-analysis for the largest subgroups of articles comprising studies on single/cluster of the trees

Table 1
Analysed studies with the year of publications, main methods applied, city of the investigation, climate of the cities, surfaces over which the trees were grown, species investigated, the species characteristics measured (DBH = diameter at breast height, LAI = Leaf Area Index, LAD = Leaf area density, Method: ΔST = Surface Temperature Difference, P = Porometic Data, S = Sapflow Data).

No	Study & Year	Method	City	Climate	Surface	Species	Provided
Cooling by Shading							
1	Lin and Lin (2010)	ΔST	Taipei City, Taiwan; China	Cfa	Grass	*Ulmus parvifolia*; *Pterocarpus indicus*; *Sapium sebiferum*; *Ficus microcarpa*; *F. elastic*; *Pistacia chinensis*; *Alstonia scholaris*; *Liquidambar formosana*; *Bischofia javanica*; *Cassia fitula; Bambusa vulgaris; B. ventricosa*	LAI; Crown diameter, leaf colour, leaf thickness
2	Mascaró (2012)	ΔST	Passo Fundo, Brazil Brasil	Cfa	Grass	*Caesalpinia peltophoroides*	
4	Armson et al. (2012)	ΔST	Manchester, GB	Cfb	Asphalt, Grass	*Tilia europea*	LAI, tree height, crown diameter
5	Armson et al. (2013)	ΔST	Manchester, GB	Cfb	Asphalt	*Crataegus laevigata*; *Sorbus arnoldiana*; *Prunus Umineko*; *Pyrus calleryana*; *Malus Rudolph*	LAI, tree height, crown diameter
6	Millward et al. (2014)	ΔST	Toronto, Canada	Dfb	Building	*Morus alba*; *Acer saccharinum*; *A. saccharum*; *Quercus robur*, *Gleditsia triacanthos*; *Betula pendula*; *Tilia cordata*; *Fraxinus pennsylvanica*	LAI, tree height, crown diameter
7	Berry et al. (2013)	ΔST	Melbourne, Australia	Cfb	Building	*Fraxinus excelsior*; *Angophora floribunda*	LAI, tree height, crown diameter
8	Parker (1987)	ΔST	Miami, Florida	Aw	Building	*Ficus elastica*	Crown diameter
9	Gillner et al. (2015b)	ΔST	Dresden, Germany	Dfb	Asphalt	*Corylus corluna*; *Ginko biloba*; *Liriodendron tulipifera*; *Tilia cordata*; *Ulmus x hollandica*	LAI, tree height, crown diameter
10	Napoli et al. (2016)	ΔST	Florence, Italy	Csa	Asphalt, Grass	*Acer negundo*; *Aesculus hippocastanum*; *Cedrus deodar; Celtis australis*; *Pinus pinea*; *Platanus occidentalis*; *Prunus cerasifera*; *Olea europea*; *Ligustrum ludicum*; *Tilia cordata*	LAI, tree height, crown diameter
11	Rahman et al. (2018)	ΔST	Munich, Germany	Dfb	Asphalt, Grass	*Robinia pseudoacacia*; *Tilia cordata*	LAI, tree height, crown diameter
12	Devia and Torres (2012)	ΔST	Santa Marta City, Brasil	Bsh	Asphalt	*Terminalia catappa; Prosopis juliflora; Meliccoca bijuca; Platysmincium pinatum; Enterolobium ciclocarpum*	Tree height, crown diameter
13	Massetti et al. (2019)	ΔST	Florence, Italy	Csa	Asphalt	*Tilia vulgaris*	LAI, tree height, crown diameter
Cooling by Transpiration							
1	Fini et al. (2009)	P	Como, Italy	Cfb	Grass	*Acer platanoides* 'Summershade'*; A. platanoides* 'Deborah'*; A. platanoides* 'Emerald Queen'*; Tilia cordata; T. europea; T. platyphyllos; T. tomentosa*	DBH, tree height
2	Forrai et al. (2012)	P	Budapest, Hungary	Dfb	Grass	*Acer negundo; A. negundo* 'Kelly's Gold'*; A. platanoides; A. platanoides* 'Krimson King'*; A. pseudoplatanus; Fraxinus excelsior* 'Westhofs Glorie'; *Tilia cordata; T. tomentosa; T. tomentosa* 'Balaton'; *T. tomentosa* 'VI'	
3	Gillner et al. (2015a)	P	Dresden, Germany	Dfb	Asphalt	*A. platanoides; A. pseudoplatanus; Platanus x hispanica; Quercus rubra; Tilia platyphyllos*	DBH, tree height
4	Gillner et al. (2015b)	P	Dresden, Germany	Dfb	Asphalt	*Aesculus x carnea; Corylus corluna; Ginkgo biloba; Liriodendron tulipifera; Tilia cordata* 'Greenspire', *Ulmus x hollandica*	LAD, Crown diameter, DBH, tree height
5	Jiao et al. (2017)	P	Beijing, China	Dwa	Grass	*Ginkgo biloba; Populus tomentosa*	DBH, tree height
6	Konarska et al. (2016)	P	Gothenburg, Sweden	Dfb	Grass, Asphalt	*Acer platanoides; Aesculus hippocastanum; Betula pendula; Fagus sylvatica; Prunus serrulata; Quercus robur; Tilia cordata*	DBH, LAI, crown diameter, tree height
7	Leuzinger et al. (2010)	P	Basel, Switzerland	Dfb	Asphalt, Grass	*Acer platanoides; Aesculus carnea; A. hippocastanum; Platanus acerifolia; Tilia cordata; T. platyphyllos; T. tomentosa*	
8	McCarthy et al. (2011)	P	Los Angeles, USA	Csa	Grass	*Brachychiton discolor, B. populneus, Eucalyptus grandis, Ficus microcarpa, Jacaranda chelonia, Gleditsia triacanthos, Lagerstroemia indica; Koelreuteria paniculata*	DBH
9	Rahman et al. (2011)	P	Manchester, UK	Cfb	Grass, Asphalt	*Pyrus calleryana*	DBH, LAI, crown diameter, tree height
10	Rahman et al. (2017a)	S	Munich, Germany	Dfb	Grass, Asphalt	*Tilia cordata*	DBH, LAI, tree height, crown diameter
11	Rahman et al. (2018)	S	Munich, Germany	Dfb	Grass	*Tilia cordata; Robinia pseudoacacia*	DBH, LAI, tree height
12	Stratopoulos et al. (2018)	S	Munich, Germany	Dfb	Grass	*Acer platanoides; A. campestre; Carpinus betulus* 'Fastigiata'*; Ostrya carpinifolia; Tilia cordata* 'Greenspire'*; T. tomentosa* 'Brabant'	DBH,LAI, crown area
13	Stratópoulos et al. (2019)	S	Munich, Germany	Dfb	Grass	*Acer platanoides; A. campestre; Carpinus betulus* 'Fastigiata'*; Ostrya carpinifolia; Tilia cordata* 'Greenspire'*; T. tomentosa* 'Brabant'	DBH

Table 2
Statistical characteristics of ΔST and E of the reviewed studies along with numerical variables LAI, leaf area, height, crown diameter, leaf thickness, SLA and leaf size. For E, values were standardized resulting in E_{norm} (see section 4 statistics), these standardized values were provided as well in italic (*second row at cooling by transpiration*) for thoroughness. Here, ΔST = Temperature difference between shaded and unshaded areas, E = Evapotranspiraton, E_{norm} = standardized evapotranspiration, n = number of datasets for each parameter, SD = standard deviation, LAI = leaf area index, dbh = diameter at breast height, SLA = specific leaf area.

	Cooling by Shading			Cooling by Transpiration		
	n	Mean	SD	n	Mean	SD
***ΔST** [°C]/**E** [g H_2O m^{-2} min^{-1}*	**59**	**9.40**	**4.75**	**100**	**1.74**	**0.98**
***E_{norm}** [g H_2O m^{-2} min^{-1}*				***79***	***3.30***	***3.31***
LAI [m^2 m^{-2}]	49	3.19	1.13	23	4.08	1.47
				23	*4.08*	*1.47*
Leaf area [m^2]	34	76.43	13.73	76	73.48	49.61
				56	*69.34*	*36.55*
Dbh [cm]	–	–	–	79	19.58	20.33
				79	*19.58*	*20.33*
Height [m]	47	10.63	5.46	61	7.99	5.70
				61	*7.99*	*5.70*
Crown diameter [m]	58	7.74	4.90	26	4.86	3.97
				26	*4.86*	*3.97*
Leaf thickness [mm]	36	0.24	0.17	51	1.54	0.48
				41	*1.50*	*0.47*
SLA [cm^2/g]	31	175.92	81.56	66	218.00	69.08
				51	*227.00*	*61.05*

with the same species from urban parks, streets and squares. We also calculated the effect size of each individual trait for ΔST and E, respectively. In the case of two groups, we therefore used Cohen's effect size (d) calculation by deriving the ratio of the mean differences between two groups, and the standard deviation. In the case of more than two groups, we used the approach provided by Cohen [46].

ΔST was evaluated based on variations in climate (Continental, Mediterranean, Oceanic, sub-tropical, other), shaded surface (grass, asphalt and building walls), habitat (species-rich forests H3, steppes & dry forests H6, wetlands H2, wet & cold forests H7, others including H4 and H9), plant functional type (evergreen, coniferous, deciduous), growing size (tall, medium, small), wood anatomy (ring, diffuse porous, other), leaf colour (green, dark green, other), leaf shape (compound, needle, simple), crown shape (columnar, oval/round, pyramidal), leaf thickness (thin: <0.15 mm, medium: 0.15–0.3 mm, thick: >0.3 mm), and canopy density in terms of LAI (low: <2, medium: 2-4, high: >4). In addition, leaf hairiness (some, dense, no) was only analysed for E; however, plant functional type, crown shape were excluded due to minor expected relationships and missing data sets. All species were classified by the climate zone where the study was conducted after Köppen and Geiger [38], the surface type beneath the tree, the habitat that the species originates from and the possible growing size in three categories (both after Roloff and Bärtels [40]). The climate categories included tropical savanna (Aw - Miami, USA), humid subtropical (Cfa - Taipei, Taiwan; Passo, Brazil), Oceanic (Cfb – Manchester, UK; Melbourne, Australia; Como, Italy), Warm summer continental (Dfb – Toronto, Canada; Basal, Switzerland; Gothenburg, Sweden; Dresden and Munich, Germany; Budapest, Hungary), Mediterranean hot summer (Csa – Florence, Italy; Los Angeles, USA), Semi-arid (Steppe) (Bsh – Santa Marta, Brazil), Hot summer continental (Dwa – Beijing, China) (Table 1).

For ΔST, sun zenith angle and the morphological characteristics of the same species grown in different settings are also important. Considering the fact that most of the primary branches are horizontally oriented and the highest transmissivity occurs around mid-day with low sun altitudes, we considered only the values pertaining to the mid-day to early afternoon. The added advantage is that the effect of canopy

Table 3
Trait list analysed in this meta-analysis with number of datasets (n) available per trait for shading and transpiration analysis (NA stands for data not available).

Variable	Variation	Analysed	n
Climate after Köppen and Geiger (1930–1939)	Cfa - Subtropical	ΔST/ E_{norm}	13/NA
	Cfb - Oceanic		17/30
	Csa - Mediterranean		14/8
	Dfb, Dwa - Continental		9/41
	Other (Aw, Bsh)		6/NA
Surface Type	Asphalt	ΔST/ E_{norm}	24/18
	Building		12/NA
	Grass		23/61
Habitat after Roloff and Bärtels (2008)	H2 - Wetlands	ΔST/ E_{norm}	8/4
	H3 – Species-Rich Forests & Woodlands		12/30
	H6 – Steppes & Dry Forests		13/17
	H7 – Wet & Cold Forests		-/9
	Other (H4,H9)		6/-
Cultivar	Yes	E_{norm}	-/19
	No		-/44
Plant functional type After Peters et al.(2010)	Coniferous	ΔST/ E_{norm}	3/-
	Deciduous		43/78
	Evergreen		11/1
Leaf Color	Green	ΔST/ E_{norm}	20/40
	Dark Green		18/15
	Other		18/7
Crown Shape	Oval/Round	ΔST	39/
	Pyramidal		13/-
	Columnar		5/-
Leaf Hairiness	Dense	E_{norm}	-/9
	Some		-/36
	No		-/18
Leaf Shape	Simple	ΔST/ E_{norm}	38/73
	Needle		3/NA
	Compound		16/6
Leaf Thickness	Thin (<0.15 mm)	ΔST/ E_{norm}	20/32
	Medium (0.15–0.3 mm)		8/6
	Thick (>0.3 mm)		10/3
Growing Size after Roloff and Bärtels (2008)	Small	ΔST/ E_{norm}	14/5
	Medium		15/5
	Tall		28/53
Wood Anatomy	Diffuse	ΔST/ E_{norm}	33/37
	Other		8/27
	Ring		14/5
LAI Category	Low (<2)	ΔST	7/-
	Mean (2-4)		32/-
	High (>4)		11/-

diameter and height will cancel each other out, at midday in the summer. Otherwise, the tree species with most elliptical canopies, and hence higher aspect ratios, cast more shade relative to their canopy area because of the inclination of the sun [47]. Lastly, as in most cases urban trees are highly managed and pruned; we focused more on the shading depth (the maximum potential of ΔST) rather than shading area to make comparison among species more comprehensive. Similarly, for E we selected the values that pertained to mid-day to early afternoon since it is mostly agreed that the highest transpiration occurs and people seek the outdoor comfort mostly during that time of the day [3,47,48].

In total, 59 data sets (n) i.e. data points we have for ΔST from 50 different tree species out of 13 articles were analysed with a mean ΔST of 9.4 °C. Table 2 describes the average characteristics of the trees included in the review. The mean LAI of all the trees analysed for ΔST was 3.2, together with an average leaf area of 76 m^2, tree height of 10.6 m, crown diameter of 7.7 m, leaf thickness of 0.24 mm and SLA of 176 cm^2/g. Average tree transpiration E (n = 100 from 41 different species out of 13 articles) was 1.74 g H_2O m^{-2} min^{-1} leaf area. The mean LAI of all the trees analysed for E was 4.1, together with an average dbh of 19.6 cm, height of 8.0 m, leaf area of 73.5 m^2, crown diameter of 5 m, leaf thickness of 1.54 mm and SLA of 218 cm^2 g^{-1} and a crown diameter of 4.9 m. Fewer data sets of E were available than LAI. To ensure data uniformity, data on E were further standardized in a later step (please see section *4 Statistics*). For thoroughness, standardized E (E_{norm}) were included in Table 2 as well in a second row in italic letters. After standardization, datasets (n) of E_{norm} were reduced to 79 with a mean value of 3.3 g H_2O m^{-2} min^{-1}. LAI, dbh, height and crown diameter datasets in the transpiration section were not reduced by standardization inducing identical mean and SD values. However, datasets for leaf area, leaf thickness and SLA were reduced, resulting in slightly changed mean and SD values (see Table 2). Analysed variables along with the variations used for analysing ΔST or E_{norm} and the number of data sets are described in Table 3.

4. Statistical analyses

4.1. Data transformation

To unify the included studies on E, we harmonized both porometric transpiration data (E; mmol m^{-2} s^{-1}) and sap flux data measured at the stem (J_S; g H_2O cm^{-2} min^{-1}) by scaling them to an average value of transpiration per m^2 leaf area (E_L).

Porometric data, which is usually measured at sunlit leaves, was initially converted to g H_2O min^{-1} by multiplying with the molar weight of H_2O [48]. Further conversion was directed by findings of Konarska, Uddling, Holmer, Lutz, Lindberg, Pleijel and Thorsson [49], assuming that for isolated urban trees, one third of the canopy is shaded and two thirds are sun exposed and that sunlit leaves transpire at three times as high rates as leaves in the shade (eq. (1)).

$$E\frac{mmol\ H_2O}{m^2\ leaf\ area\ s} = E\frac{g\ H_2O}{m^2\ leaf\ area\ min} = \frac{2}{3}E + \frac{1}{3}\frac{E}{3} = E_L\frac{g\ H_2O}{m^2\ leaf\ area\ min} \quad (1)$$

Stem xylem flux data was subset for summer (June, July, August) and times between 12h00 and 16h00, converted into transpiration per unit canopy area (E_C) by multiplying by the ratio of cross-sectional sapwood area to projected canopy and then scaled to E_L by dividing E_C by the leaf area index (LAI) [26] (eq. (2)).

$$J_S\frac{g\ H_2O}{cm^2\ sapwood\ area\ min} = E_C\frac{g\ H_2O}{m^2\ canopy\ area\ min} = E_L\frac{g\ H_2O}{m^2 leaf\ area\ min} \quad (2)$$

We found very strong negative correlations of E_L with dbh (r = −0.53, p < 0.001) and height (r = −0.62, p < 0.001) (Fig. 1), as parameters related to tree age and leaf area, the data for further analysis were normalised with mean and standard deviation of dbh (eq. (3)).

$$Enorm = \frac{\left(\frac{standard\ E}{mean\ standard\ E}\right)}{sd\ standard\ E} \quad (3)$$

where standard E = E_L/dbh.

4.2. Meta-analysis

All further analyses were carried out using R, version 3.3.3 [50]. First, we scrutinized which parameters had the strongest influence on ΔST and E_{norm} across all cities and climate zones. Where necessary, data were log or power transformed in order to correct for data displaying heteroscedasticity. For the following statistical analysis, we applied linear mixed models of the form:

$$log(Yijk) = a0 + log(Xijk) + a1 \times Variableijk + b0 + b1 \times Variableijk + cij + dik + \varepsilon ijk, \quad (4)$$

with Y_{ijk} as ΔST or E_{norm} for the jth of n_i observations, a_0 as the intercept, a_1 as the intercept of the tested categorical variables (surface, climate, LAI category, leaf thickness, etc.) named as $Variable_{ij}$, b_0 as fixed effect, b_1 as fixed effect of $Variable_{ij}$, X_{ij} as the tested numerical variable such as LAI, SLA and leaf area, c_{ij} as random effects species within city and εij as errors (eq. (4)). Specific forms of each applied equations are provided in the Appendix 1. To summarize the variables of the equations, $a_1, \ldots, a_n$ and, $b_1, \ldots, b_n$ are the fixed effects with the "*a*" parameters are components of the intercept and the "*b*" parameters are components of the slope, respectively. In all models, the indexes ***i, j, k*** represent the city, species and surface, respectively. The "c" parameters are random effects, which are assumed to be normally distributed. These random effects cover statistical dependencies, which are due to the nested data structure. The random effect c_i covers city (and as such species) specific deviations from the general slope. The errors εij are assumed independent identically distributed.

The effects of the site conditions of measurement (climate, surface type), the origin of species (habitat) and their traits (plant functional

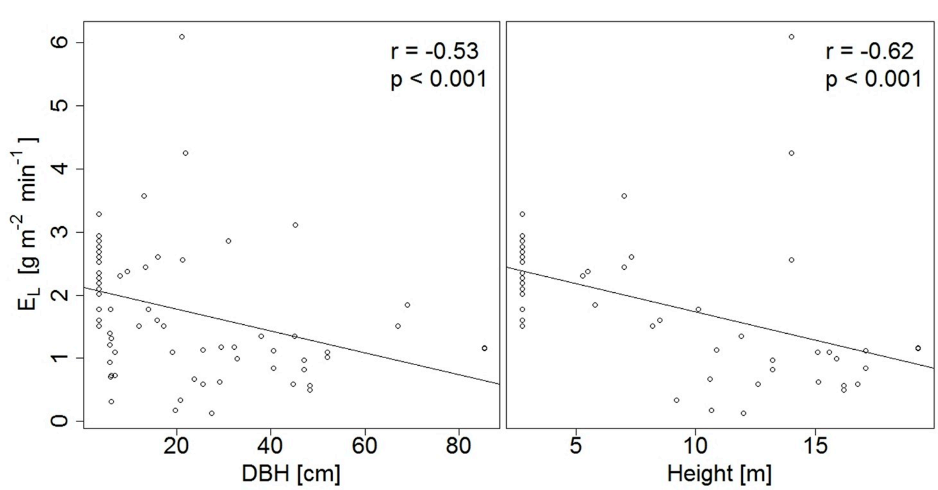

Fig. 1. Spearman correlations between transpiration per m^2 leaf area (E_L) and the age-related parameters of diameter at breast height (DBH, left) and height (right).

type, growing size, wood anatomy, crown shape, leaf colour, leaf hairiness, leaf shape, leaf thickness, LAI category) on ΔST and E_{norm} were analysed. Therefore, data were assessed on normal distribution by Shapiro-Wilk test and homogeneity of variances by Levene-Test. ΔST data followed these assumptions, so one-way ANOVA with Tukey post-hoc tests were applied. E_{norm} data only partly followed the model assumptions, hence when not meeting assumptions we used the Kruskal-Wallis H test and the Wilcoxon rank sum test with Bonferroni-Holm p-value adjustment. In most cases, observations represented very different distributions. Results from these tests were regarded as tests of dominance between distributions, rather than of differences between medians or means, respectively.

5. Comparative analyses of the results

5.1. Shading effect

ΔST was first related to LAI with surface as added factorial variable and then with climate as added factorial data (Fig. 2). While ΔST increased with LAI, the highest differences were found over asphalt, the lowest over grass and intermediate differences over building walls. The ΔST also increased when we added Köppen-Geiger climate classification as factorial variable; however, the increase was less steep. Greatest differences in ΔST were found for cities in tropical, and steppe, and Mediterranean climates, while lowest differences were observed for subtropical cities. Cities with a Continental and Oceanic climate showed an intermediate ΔST over LAI.

Analysis of several categorical parameters highlighted marked influences of environmental variables and morphological traits on ΔST (Fig. 3a and b). The climate zone showed a significant effect on ΔST with the highest differences found for Mediterranean climate zones and the category "other" (including tropical and steppe climate). The smallest ΔST was found for studies conducted in cities with subtropical (on average 7 °C lower in ΔST than Mediterranean climate) and Continental climates (5 °C less ΔST than Mediterranean cities). In terms of the below-canopy surface cover, the ΔST over asphalt to grass was on average 6.2 °C and to building 5.2 °C higher. No significant differences were found between building and grass surfaces (ΔST difference between grass and building was 1.1 °C on an average).

All further analyses of traits showed only few significant differences for ΔST. The greatest ΔST were found for species from species-rich forests and woodlands (H3), of coniferous functional type, typically of small sized and semi-ring/semi-diffuse porous species and non-porous species compared to ring porous species. Moreover, the greatest ΔST were found for species with green leaf colour, for needle tree species, species with pyramidal crown shapes, thin leaved species and trees with high LAI values. For growing size, leaf thickness and LAI categories, significant differences between variations were found. Small trees provided on average 1.5 °C and 4.1 °C higher ΔST than tall and medium sized trees respectively. The effect of the LAI category on ΔST was almost similar for high and medium LAI with a difference of 1 °C on average. However, under the shade of trees with low LAI values, ΔST was on average 5 °C lower than under the shade of trees with high LAI values. Surprisingly, species with thin leaves provided the highest ΔST, compared to medium (4.2 °C) and thick leaves (2.5 °C lower), with thin and medium leaves being significantly different.

A further statistical analysis of both models can be found in Tables S1a and S1b of the Appendix 1. All model parameters were highly significant. Similar to the Fig. 2, the linear mixed models illustrated that the surface type had significant influence on ΔST with the greatest effect over asphalt. The climate zone of the city also showed significant influence on **Δ**ST with Oceanic and Mediterranean regions revealing the strongest correlation with **Δ**ST. Relationships between LAI and surface as well as crown diameter and climate, respectively were tested but proved non significant and were therefore removed from the models.

Other numerical data such as height, leaf area and SLA were found to have no significant correlation with ΔST. Effects of plant functional type and morphological traits (leaf and crown) on surface cooling were also tested with mixed models. Significant results were found for leaf shape, LAI category and growing size (results can be found in Tables S2, S3 and S4 in Appendix 1). While in case of trees with compound leaves, ΔST increased over crown diameter, in case of trees with needle leaves, ΔST decreased steeply over crown diameter, which might be related to the typical pyramidal shape of needle leaved trees. For simple leaves, a slight decrease of ΔST over crown diameter was found. With added LAI category, on the other hand, ΔST was rather static along with the increase of crown diameter for all three categories (low, medium, high). Trees with high LAI provided the best shading and trees with lower LAI had the least shading effect. For the growth size of the trees, significant effects on ΔST were found altogether. The greatest values of ΔST were found for small trees; however, the difference between medium and tall trees was not significantly different.

5.2. Transpiration cooling

The effect of tree structural data such as leaf area and SLA was tested for E_{norm} (Fig. 4). For trees grown in the Mediterranean climate, E_{norm} decreased with leaf area (around 0.3 g m^{-2} min^{-1} per 100 cm^2 leaf area), while trees grown in Oceanic climate showed an increase of E_{norm} at very low values of leaf area and relatively stable E_{norm} values towards

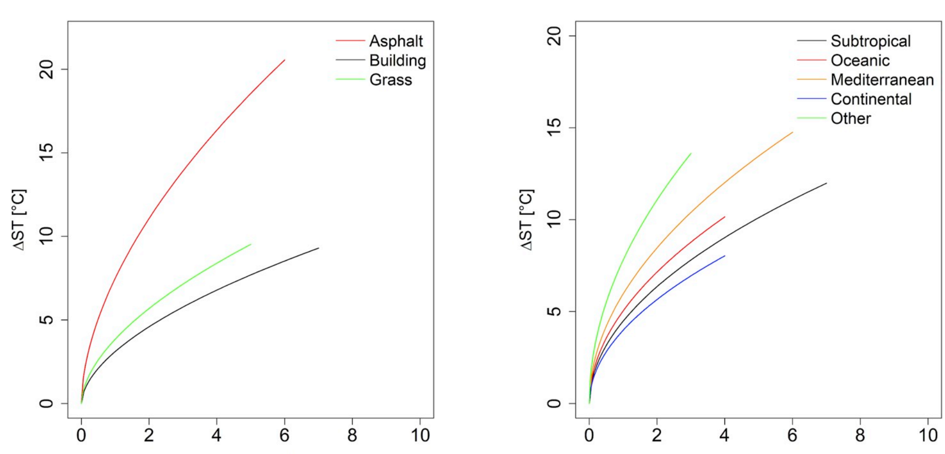

Fig. 2. The surface temperature difference between shaded and unshaded areas (ΔST) in relation to LAI over asphalt, building and grass surface (left) and in relation to LAI of urban tress grown in subtropical, oceanic, Mediterranean, continental and other climates (right).

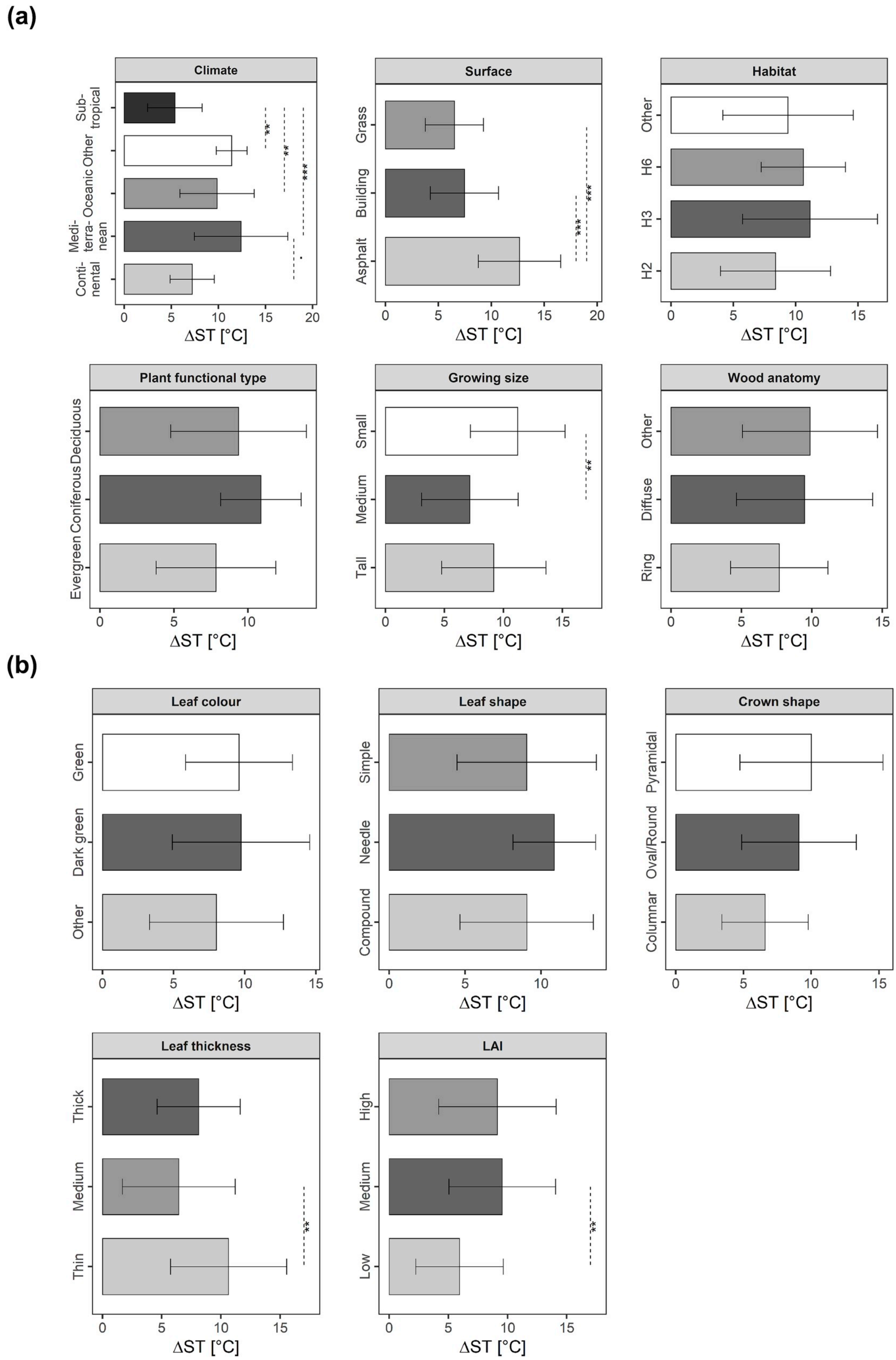

Fig. 3. a) Comparing the effect of climate, surface, habitat, plant functional type, growing size and wood anatomy on ΔST with standard deviation and significance indication derived by one-way ANOVA (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$). b) Comparing the effect of leaf colour, leaf shape, crown shape, leaf thickness and LAI category on ΔST with standard deviation and significance indication derived by one-way ANOVA (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$).

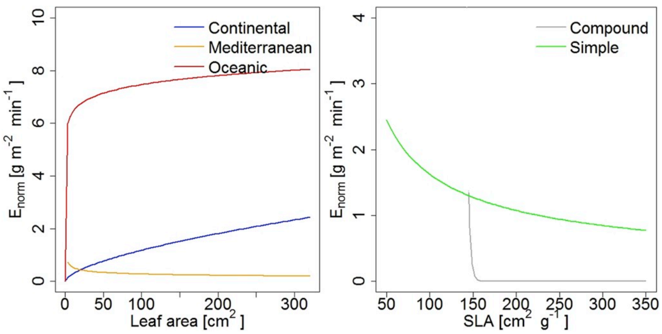

Fig. 4. Graphical representation of linear mixed-effects modeling E_{norm} in response to leaf area and climatic zone as well as with specific leaf area (SLA; cm^{-2} g^{-1}) and leaf shape.

bigger sizes (around 3 g m^{-2} min^{-1} per 100 cm^2). Under a continental climate, E_{norm} steadily increased with leaf area (around 1 g m^{-2} min^{-1} per 100 cm^2). The highest E_{norm} was reported for trees grown in Oceanic climate compared to Continental or Mediterranean climate. For leaf shape, a trend of decreasing E_{norm} with increasing SLA was found (Fig. 4). Compound leaves showed lower SLA in comparison to simple leaves. For both types of leaves, transpiration decreased with increasing SLA, but E_{norm} was higher for simple leaves in comparison to compound leaves.

Statistical results of linear models shown in Fig. 4 are given in Tables S5a and S5b in Appendix 1. There was a very strong effect ($p < 0.001$), depending on where the measurements were conducted and of leaf area. With increasing leaf area, E_{norm} increased as well. The trees grown in Oceanic climate showed the highest E_{norm}, followed by Mediterranean climates, albeit this effect was not significant. Adding climate classification to leaf area resulted in a negative effect on cooling, indicating that the increase of E_{norm} with higher leaf area of trees in Oceanic and Mediterranean climate zones could reduce the E_{norm} slightly. The mixed effect of SLA and leaf type was evident, albeit less strong ($p < 0.1$) in comparison to the other models shown. Simple leaves provided higher E_{norm} than compound leaves ($p < 0.07$). This group, though, had high E_{norm} values at low SLA, became relatively stable and low starting from SLA values of around 150 cm^{-2} g^{-1}. Moreover, simple leaves showed a more continuous E_{norm} decline with increasing SLA. Further models with numeric variables such as LAI, leaf thickness, tree height and crown diameter as well as with categorical data on leaf color, habitat, growing size, and leaf thickness resulted in non-significant models and therefore are not shown.

Climate showed a strong effect ($p < 0.001$) on E_{norm} (Fig. 5). Average E_{norm} was the highest (6.96 g H_2O m^{-2} min^{-1}) in Oceanic climate in comparison to Continental (1.00 g H_2O m^{-2} min^{-1}) or Mediterranean (0.55 g H_2O m^{-2} min^{-1}) climate. Moreover, trees planted in grass lawns with access to larger soil volume showed significantly higher E_{norm} than those grown on cut-out pits ($p < 0.001$). The values of E_{norm} were on average ten times higher for trees planted over grass (4.15 g H_2O m^{-2} min^{-1}) compared to trees planted in cut-out pits (0.44 g H_2O m^{-2} min^{-1}). Moreover, the native habitat was found to play an important ($p < 0.05$) role for E_{norm}. Trees originating from temperate and resource-rich forests and woodlands (H3) showed the highest E_{norm} (average 4.50 g H_2O m^{-2} min^{-1}) values, followed by trees originating from steppes and dry woodlands (H6) (3.35 g H_2O m^{-2} min^{-1}) and wet and cold forests (H7) (2.86 g m^{-2} min^{-1}) respectively.

Concerning the leaf traits, trees with thin leaves (<0.15 mm) showed significantly ($p < 0.05$) higher E_{norm} with an average of 4.31 g H_2O m^{-2} min^{-1}, than trees with leaf thicknesses with values between 0.15 and 0.3 mm. Moreover, leaf type also showed a significant effect on E_{norm}. Trees with compound leaves showed significantly ($p < 0.05$) lower E_{norm} (0.46 g H_2O m^{-2} min^{-1}) in comparison to trees with simple leaf shapes (3.54 g H_2O m^{-2} min^{-1}). The effect of leaf hairiness was not clear ($p = 0.47$), but densely haired leaves showed the lowest E_{norm}. Even though the effect of leaf colour was also not significant ($p = 0.12$), there was evidence of a trend towards higher E_{norm} with increasing chlorophyll

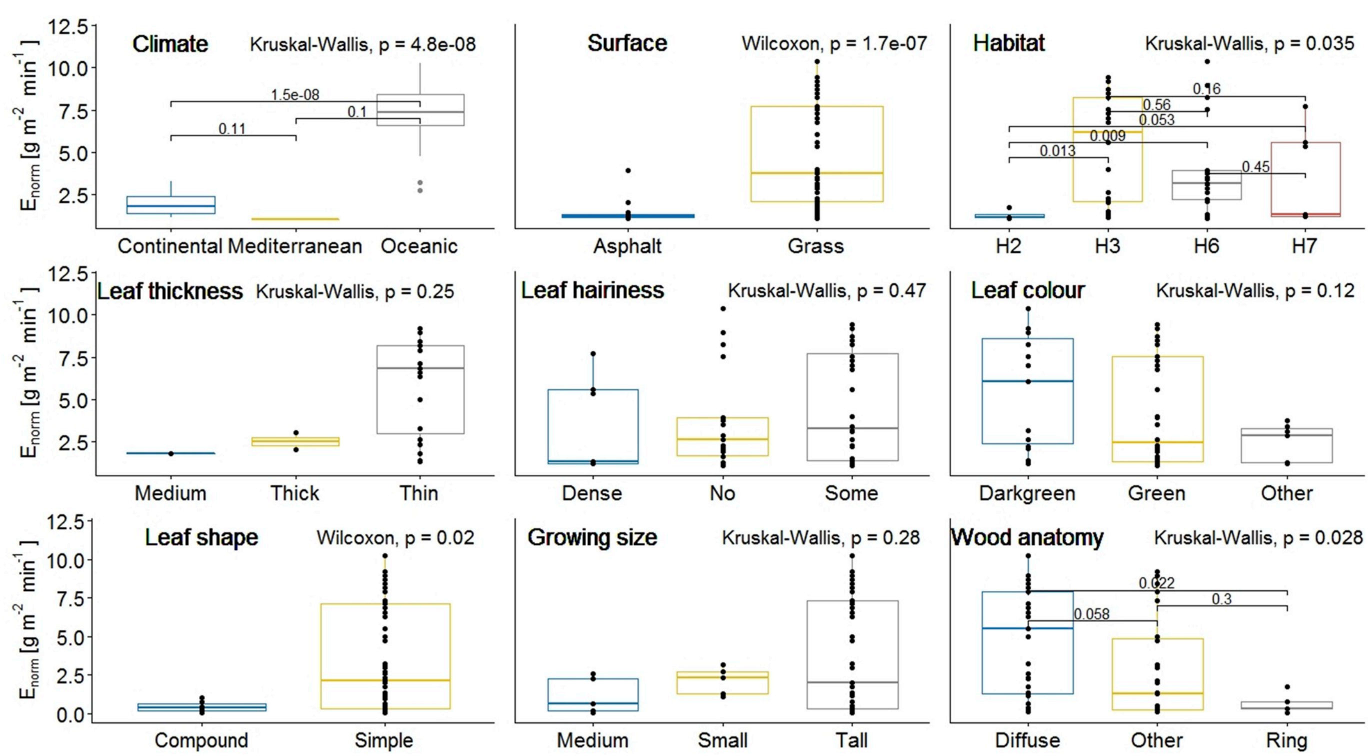

Fig. 5. Boxplots comparing normalised transpiration rates (E_{norm}; g m^{-2} min^{-1}) between various specifications of parameters concerning the site conditions of measurement, the origin of species, and their traits. The p values reflect the results of the Wilcoxon test and the Kruskal-Wallis H test including post-hoc analyses. Specifications were only accepted for analysis in case of minimum four valid observations.

content and lower E_{norm} for pale-yellow-, grey- or light green leaves, summarized under the term "others". Trees reaching more than 20 m of height ("tall") showed the highest E_{norm} (3.84 g H_2O m^{-2} min^{-1}) compared to the medium (1.15 g m^{-2} min^{-1}) and small sized trees (2.14 g m^{-2} min^{-1}); however, the difference was not statistically significant ($p = 0.28$). Finally, the wood anatomy also showed a significant ($p < 0.05$) effect on E_{norm}. Diffuse porous trees showed significantly higher ($p < 0.05$) E_{norm} with on average 4.62 g H_2O m^{-2} min^{-1} than ring porous species (0.65 g H_2O m^{-2} min^{-1}). Intermediate forms between diffuse and ring porous wood anatomy and non-porous wood ("others") had E_{norm} values in between other two categories.

6. Discussion

This systematic review was designed to evaluate different urban tree species' characteristics to suggest the relative strength of variables in terms of cooling benefits. A summary of the meta-analysis for shading and transpiration air-cooling is shown in Fig. 6. There is a consensus regarding decreasing air temperature with increasing tree density [8,51,52]. Nevertheless, if we consider the comparative cooling capacities varies up to 4 times between species [25,53–55]; mitigation of UHI using greenspaces can be more effective by tree selection. We focused on the subset of studies investigating species grown in different climates and under different growth conditions with inherent morphological and physiological traits, which may be used to guide urban greening strategies. Most of the studies reviewed in this research have investigated the effect of single or clusters of trees of the same species in reducing the thermal load within the same urban area and support the idea that urban trees can have significant effects, at least at micro-scale. It should be noted that the potential confounding variables in the real urban environment is difficult to control. Therefore, we tried to reduce the variabilities by using cities (as well all the related uncertainties) as random variables in our mixed model analysis. Field studies investigating matured trees were the primary source of information for this review; however, some studies with "rare" anatomical variables (such as Lin and Lin [53]) and leaf traits from the "TRY" database were included to arrive

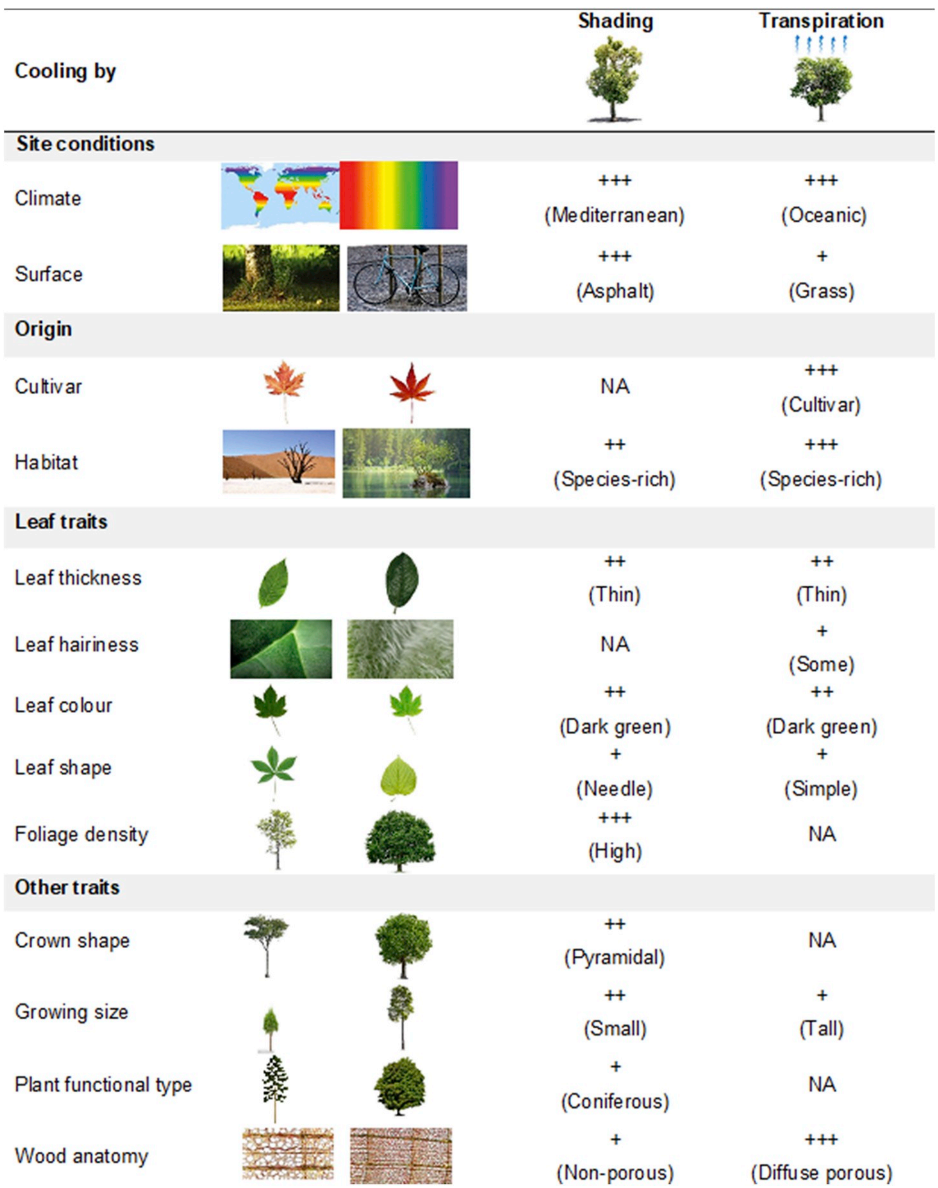

Fig. 6. Summary of the findings considering shading and transpiration air-cooling for all analysed site conditions and species traits. The species' traits were ordered according to their effect size for shading and transpiration. The ranking of species' traits in relation to shading and transpiration was from +++ (very high effect) to + (low effect), the best categories are in brackets.

at some robust conclusions.

The cooling effect can be easily explained in terms of the energy balance of the individual surfaces regarding shade, surface albedo and the state of the water availability during the daytime [56]. There seems to be an inverse relationship between ΔST and E_{norm}. Higher radiation intensity associated with higher atmospheric demand as well as lower soil moisture during the sampled days in low latitude cities might result in higher sensible heat from the ground but lower latent heat flux from trees compared to the high latitude cities, which could partly confirm and support our results [16]. Soil moisture seems to have the opposite effect in terms of ΔST: the dry Mediterranean and steppe & tropical climates (termed as "other") showed the highest ΔST and the wet climate such as subtropical (mostly dominated by the study by Lin and Lin [53] since Taipei City receives more than 2000 mm of annual rainfall) and continental climate showed the lowest ΔST. However, wet zones showed more boundary layer air-cooling potential compared to the dry zones. This is also in line with the general predictions of a maximum air-cooling of 3 °C from trees in parks in mid-latitude cities [22]. The effect was almost double up to 6 °C in Gothenburg, Sweden (Köppen-Geiger climate classification: Cfb) [57] with Continental to Oceanic climate. However, our meta-analysis did not find strong support for the study by Spronken-Smith and Oke [56] who reported similar temperature differences in the parks of Sacramento (dry-summer, subtropical climate) and Vancouver (maritime temperate). Another exception was the study of Shashua-Bar and Hoffman [23] as they reported the cooling effect of trees to be greater on days with warmer temperatures while studying the effect of trees in Tel Aviv. Moreover, the persistent scarcity of empirical studies particularly on the tropical, sub-tropical or other hotter and drier climates might have biased our results. For instance, only two out of 26 studies analysed were from subtropical and tropical climate (Table 1). Moreover, long-term observations of cooling potentials of urban trees with spatial variations were also lacking for warmer and drier climates. Therefore, the obtained results of higher potentials of ΔST and lower potentials of E_{norm} from those climates compared to Continental and Oceanic climates might have been biased.

6.1. Surface cooling

There is a consensus about the effect of tree shade on surface cooling. Surprisingly little research has been undertaken to quantitatively characterize the effect of shade of different tree species [13]. By calculating effect sizes of individual parameters, our meta-analysis highlighted the order of relative contributions for ΔST as climate > below canopy surface > growing size > leaf thickness > LAI > crown shape > plant functional type > habitat > wood anatomy > leaf shape > leaf colour. As discussed, climate is the foremost important aspect in determining the potential of ΔST. Our study showed that both surface type and shade greatly affect ΔST. Depending on the grass evapotranspiration, ΔST over grass surfaces are predicted to be smaller compared to the built surfaces [58]. Next, the influence of tree size on ΔST appeared to be related to the fact that taller trees have narrower canopies, while smaller trees have wider and denser canopies. This can also be seen for round shaped tree crowns that provide better surface cooling since they cast shade on a specific surface point for a longer time [13]. Another reason may be that the grounds under taller trees (hence higher branch free trunks) are subjected to bigger volumes of hot air from the surrounding areas to have higher ground heat flux. Counterintuitively, the crown diameter showed a rather symmetric pattern on the maximum surface cooling potential.

The effect of leaf thickness on surface cooling was against the common assumption of thick leaves providing better shading. There could have been a number of reasons. For instance, usually thick leaved species are light-demanding [59], fast growing and have less dense canopies. On the other hand, thin leaved species are often climax species with dense canopies or the higher amount of long wave radiation fluxes from thick leaves increased the downward ground heat flux. Overall, LAI is the central criterion in determining the degree of ΔST over paved surfaces [54,55]. Consequently, Hardin and Jensen [60] showed that every unit of LAI increase reduces surface temperature by 1.2 °C. Gillner, Vogt, Tharang, Dettmann and Roloff [61] showed that every unit of LAD (leaf area density in m^2 m^{-3}) decrease, increased asphalt surface temperature by 4.6 °C. However, the interactive effect of LAI and surface temperature is complex, especially when ΔST is calculated over transpiring grass surfaces or built surfaces with lower thermal masses than asphalt. To further complicate the issue, available below canopy soil moisture can vary with microclimatic demand, water use efficiency (WUE), LAI of plants in the system [62,63]. The non-significant relationship between ΔST and LAI over transpiring grass surface has also been comprehensively summarized in previous research such as Lin and Lin [53], Napoli, Massetti, Brandani, Petralli and Orlandini [54], Massetti, Petralli, Napoli, Brandani, Orlandini and Pearlmutter [64]. This might be the reason, when we aggregated our ΔST values (grass, asphalt and building wall), that LAI was ranked fifth with medium effect size.

Apart from the leaf area density, the shape of the tree crown can be described by the size, aspect ratio (height to width) and the convexity or the shape of its contour [65]. With the decrease of solar angle from equator to high latitudes, beam path lengths through the crowns become increasingly longer with increasing crown flatness [66]. The dominance of tall and thin conifers at high latitudes, and flat-topped Mediterranean conifers (*Pinus pinea* and *Pinus halepensis*) as well as acacia-like trees at low latitudes [65], partly confirms and supports our values of ΔST for trees in Oceanic, Continental and subtropical climates along with the size and crown form. With higher leaf thickness and LAI, coniferous species showed higher surface temperature reductions compared to deciduous and evergreen broad-leaved species. Although most of the conifers usually have pyramidal crown shape, there was no statistically significant difference. Both pyramidal and round shaped crowns showed better surface cooling potential than trees with flattened crown. Next, the species traits related to habitat, wood anatomy, leaf shape and leaf colour with small effect size ($d < 0.20$) could have been related to the above-mentioned criteria such as ring porous species from wetlands habitat might have lower canopy density and compound leaves [67].

6.2. Transpiration cooling

The order of relative contributions for E_{norm} was tree growth (dbh and height increment) > climate > below-canopy surface cover > leaf thickness > leaf shape > habitat > wood anatomy > growing size > leaf colour > leaf hairiness. Higher annual tree growth and associated higher leaf area are the central features for providing higher transpiration cooling at least up to maturity [68] despite the fact that leaf size and SLA usually decrease with increasing tree age. However, the tree growth and E_{norm} are also related to the below canopy surface cover. Opposite to the fact that ΔST was the highest over asphalt surfaces, the lower moisture availability within the cut-out pits reduces E_{norm} significantly as shown in previous works [69,70].

Specific morphological characteristics such as leaf hairs, thickness are common life strategies adopted by trees from regions with low water availability to increase the water use efficiency (WUE) [28,67]. The relative contribution of these leaf traits to air temperature regulation, and how they can be ranked is important. The foremost leaf traits in terms of transpiration rate were leaf thickness and shape. Species with thin leaves and simple leaf shape, which often grow in resource-rich forest habitats showed higher water loss than species with thicker or compound leaves. Thick and waxy leaves are known to be a long-term adaptation to water scarcity [67] to avoid excessive water loss. The inverse relationship between leaf thickness and transpiration rate [71] and between light coloured leaves (hence more short wave reflection) and transpiration [72] is evident. In addition, leaf anatomical adjustments can also influence the WUE, for instance, Klein [73] showed that the water use of Mediterranean and semiarid species can be maintained at significantly lower leaf water potentials than trees from tropical and temperate forests. Similarly, Roloff [67] reported that tree species from dry habitats are better at lowering their water potentials to exploit additional water reserves. These findings support our review results that the water loss of trees from wetter habitats and from the Oceanic climate are higher than water loss from dry habitats and the Mediterranean climate.

In our study, diffuse porous trees had almost 4 g H_2O m^{-2} min^{-1} higher amount of water loss than the ring porous species. Ring porous species usually show a bimodal distribution of vessel diameter with wide early season vessels, which makes them more susceptible to cavitation, and narrow late-season vessels. This is why stomata of ring-porous species are more sensitive to atmospheric drivers of transpiration in comparison to diffuse porous species, which usually have more than double the density of vessels and little variation in diameter in early versus late wood [74]. Together with higher sap wood depth, they usually transpire 2-3 times more than the ring porous species [26,55, 75]. Thus, wood anatomy plays a significant role in terms of water use efficiency and drought resistance. Moser-Reischl, Rahman, Pauleit, Pretzsch and Rötzer [76] showed that the WUE of isohydric *R. pseudoacacia* was 8.11 g of dry biomass L^{-1} compared to only 1.30 g L^{-1} for anisohydric *T. cordata* trees. Studies have shown that species growing in areas of low rainfall or seasonal drought tend to have greater WUE both at the leaf and tree scale [77,78], in comparison to species from wetter habitats.

6.3. The influence of shading and transpiration on human thermal comfort

One main objective of providing shading and transpiration cooling by trees in cities is to improve human thermal comfort (HTC) during hot summer conditions. When comparing the results of the present meta-analysis to studies on HTC, again certain attributes of tree species are identified as central elements in outdoor heat reduction [79,80].

LAI can be clearly identified as the most influential driver of cooling benefits as it expresses the characteristics of foliage and its density, which directly relates to the transmissivity of solar radiation through the tree crown. Shading is consequently the most important factor for improving human thermal comfort and is most prominent during 10 a.m. and 2 p.m. [80]. During this time of the day inter-species differences seem to be the smallest [81]. Antoniadis, Katsoulas, Papanastasiou, Christidou and Kittas [79] states that the reduction of incident solar radiation by trees ranges from 79 to 94%, whereas Konarska, Lindberg, Larsson, Thorsson and Holmer [82] further specifies only 1–5% through fall of incident solar radiation for densely foliated, single trees. Examples given for especially dense tree species are i.e. *Acer saccharum* and *A. platanoides* for the USA [83] or *Bauhinia blakeana*, *Macaranga tanarius* and *Aleurites moluccana* for Hong-Kong [84]. Relating to different morphological traits, Morakinyo and Lam [85] showed that PET reductions can still differ for trees with similar LAI due to different vertical LAD (leaf area density) distribution, which should be considered while selecting tree configuration for human thermal comfort.

The second most important attribute is the canopy coverage of a tree or a group of tree. This parameter is decisive for the total surface area that is shaded and hence prevented from heating up. Lin and Tsai [86] showed that species such as *Spathodea campanulata* and *Cinnamomum camphora* had the crown diameter with the strongest effects on PET in sub-tropical Taiwan. As the spatial setups of the reviewed studies differed, different results on single trees and tree groups/tree rows were found. Most important seemed to be the premise to maximise the shaded surface area during the hottest hours of the day and plant trees accordingly. Shashua-Bar, Tsiros and Hoffman [87] for example concluded that a canopy overlap at maturity of trees planted next to each other increases their cooling effects, especially when broad-leaf trees of genus *Ficus* and *Tipuana tipu* tree species are used. Adding to this, Morakinyo and Lam [85] found out that planting double rows of trees in streets led to a greater cooling magnitude than planting trees in the centre.

Moreover, tree height seems to be a decisive factor for summer cooling, but is not dealt with as detailed as with LAI and canopy coverage and may also lead to ambiguous statements in comparison to other seasons and the need for ventilation [88]. The study of Kong, Lau, Yuan, Chen, Xu, Ren and Ng [89] for Hong Kong is the only one we know that reported about the positive effects of short trunks and large crown diameters of *Acacia confusa*, *Ficus microcarpa,* and *Peltophorum pterocarpum* on mean radiant temperature (T_{mrt}) reduction. Due to these two factors, those tree species provided shade to the built surface for a longer time than taller trees and showed higher T_{mrt} reductions.

Although the evaporative cooling effect on thermal comfort is much smaller than the cooling effect through shading, its effects for HTC regulation should not be neglected since the thermal effusivity of moistened leaves are usually higher than dry leaves [90]. On the contrary, there might be some trade-offs between these mechanisms, for instance, thick leaves might provide less transpiration but better human thermal comfort [14,25,47]. Therefore, effort should be made to combine the effects of shade and transpiration to receive the optimal human thermal comfort.

Besides that, one also needs to consider that micro-scale local variables and interlinkages of vegetation to the surrounding/other vegetation can affect the level of human thermal comfort. Massetti, Petralli, Napoli, Brandani, Orlandini and Pearlmutter [64] measured the effect of shade of around 2.5 m radius and 8 m high *Tilia* x europaea trees with LAI of 5.4 in Cascine Park in Florence, Italy on an Index of Thermal Stress over asphalt, gravel and grass (with albedo of 0.18, 0.36 and 0.25 respectively). They showed that during hot summer day a pedestrian over unshaded gravel and asphalt would experience a degree of thermal stress corresponding to “hot” conditions for 9 h during the daytime. In case of transpiring grass lawns, the “hot” perception would only be created for a brief time in the afternoon of the same day. The most significant reduction in thermal stress would be achieved through shading the asphalt when the pedestrian would be exposed to conditions defined as “comfortable” for the whole day.

7. Planting design guidelines

From this review, it can be concluded that there are no general planting design guidelines suited for all type of site conditions, as it is context-specific. However, for the optimization of the cooling benefits from urban greenspaces the following recommendations can be made:

1. Planting design should be climate and site specific. That means that in lower latitude cities with lower soil moisture content during hot summer days shading benefits might be preferred, whereas higher latitude cities with less water stress for the trees might benefit from the advantages of both transpiration and shading. These conditions will also ensure better human thermal comfort levels.
2. LAI is the central characteristic that improves all the three mechanisms – shading, transpiration and HTC - of tree cooling benefits. Therefore, trees with higher canopy density, and/or mixing of different tree species in cluster settings to create multi-layer canopies should be preferred especially over built and dry surfaces.
3. The cooling effects of trees with similar LAI values can further differ due to different vertical leaf area densities; therefore, species with higher leaf density at the lower crown should be preferred.
4. Trees with dense canopies typically smaller in size will ensure better shading effect and human thermal comfort. Therefore, at least in lower latitude cities, less pruning of lower branches wherever feasible, will ensure a better cooling benefit.
5. Tree species with dark green leaves, originating from species rich forests as well as with higher sap conducting tissues (sap wood area) will provide better cooling benefits.

6. Ensuring the vitality of trees in respect to water availability, growth conditions for above and below-ground spaces are important site-specific criteria that have to be considered.
7. The trade-offs between insulation and ventilation considering the local conditions such as SVF, street canyons, built surfaces for both day time and night time cooling with trees, shrubs and grass species should be assessed using micro-climatic models.

8. Conclusion

Our meta-analysis had the objective of identifying the characteristics of urban tree species that influence cooling potential. With higher radiation intensity, the magnitude of the shading effect will be higher for low latitude cities, whereas, with more evenly distributed precipitation over the year, transpiration cooling will be significant in high latitude cities. Even though the impact of shading will be still higher than transpiration cooling in high latitude cities [55]. Further, shaded surfaces seem to be very important. Grass surfaces absorbs less than half of the heat compared to the asphalt, consequently showed a lesser difference in surface temperatures between shaded and sunlit areas. At the same time, trees growing over grass surfaces provided 10 times more transpiration than those grown in the cut-out pits in the asphalt. A higher tree growth rate and a bigger size also allow high surface and transpiration cooling. Therefore, trees that provide dense shade at least over paved surfaces should be prioritized since every unit of LAI showed around 4 °C of surface cooling. Higher crown density and pyramidal shape coniferous and needle leaf can also be considered for shading if suited to the specific location. Similarly, origin of the species should also be given priority regarding the optimization of the benefits along with other species traits such as xylem anatomy. We showed that one single tree with diffuse porous wood anatomy, simple leaf shape and lower thickness (<0.15 mm) such as *Tilia cordata, Acer platanoides, Acer campestre* can provide boundary layer air-cooling equal to seven trees with ring/semi-ring porous wood anatomy, compound leaves with medium thickness (>0.15 mm) such as *Fraxinus excelsior, Gletitschia triacanthos*. However, even in high latitude cities especially in street settings transpiration cooling comes at a cost of higher water consumption. Regarding leaf colour, dark green leaves will improve better shading and transpiration cooling.

The reviewed studies lack standardized study protocols and methodological approaches and inclusion of site descriptions, relevant morphological and anatomical data that could have increased the comparability of studies. There are particular scarcity of empirical data on tropics and sub-tropical climate. For the human thermal comfort studies under different species there were not even enough studies available to include this cooling mechanism into the meta analysis. Tree size and growth data along with data on the shaded surface temperature and amount of water loss for different tree species is required to further strengthen our understanding regarding the tree-cooling benefit. Finally, to improve decision-making (e.g. planting schemes, species selection) modelling approaches should also be combined by incorporating empirical data.

This study pointed towards the potential of different tree characteristics to reduce urban heat. However, it is still not clear how overall green infrastructure, i.e. networks of green spaces [91], should be designed in terms of abundance, layout and distribution of a particular species or mixed species configuration in a given area. Improvements in reporting, in particular, addressing those issues would allow more robust meta-analysis and thus broaden our understanding of the potential benefits of urban greenspaces. Trade-offs between different ecosystem services, for instance, carbon sequestration and cooling benefits, bio-diversity, storm water runoff and air pollution removal potential should also be considered. Finally, the approach to consider the tree characteristics for optimal thermal benefit needs to be preceded by a comprehensive site assessment for a successful establishment especially at the advent of climate change to have the right tree at the right place [92,93]. At the same time, relationships between the drivers of biomass dynamics can be completely different based on the origin of the species. Prado-Junior, Schiavini, Vale, Arantes, van der Sande, Lohbeck and Poorter [94] showed that the dominance of certain conservative species traits (e.g., low SLA and high root to shoot ratio) might enhance productivity in particular in resource prone situation. It is therefore important to consider that different traits may become dominant in different environments [94] in terms of productivity hence thermal regulation.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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