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Review

# Street Tree Structure, Function, and Value: A Review of Scholarly Research (1997–2020)

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**Abstract:** Street trees are components of the urban forest that receive considerable attention across academic and professional disciplines. They are also one of the most common types of urban tree that people routinely encounter. A systematic review methodology was used to examine contemporary urban street tree research across natural and social science disciplines. The records collected (n = 429) were published between January 1997 and the mid-2020s and were coded for descriptive information (e.g., publishing journal and geography of study areas) as well as emergent focal research areas (e.g., ecosystem services, economic valuation, and inventory methods). From this sample, there has been considerable growth in street tree literature over time and across research themes, especially following major turning points in the field of urban forestry. Regulating ecosystem functions/services of street trees, especially cooling, has had the greatest attention in the literature, but other robust areas of research also exist, including the utility of pruning waste as construction materials, the benefits and disservices to human health and safety, and indicators of environmental (in)justice. Opportunities for future research and implications for research and practice are also discussed.

**Keywords:** street tree; literature review; structure; function; value



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## 1. Introduction

Urban landscapes are the everyday environment of the majority of the global population (55%), including nearly 80% of European and US residents, and between 50 and 80% of residents living in Eastern Europe, East Asia, North and Southern Africa, and South America [1]. Streets are, in turn, the most prominent type of publicly accessible urban landscape [2], and trees have long been understood as essential elements of streetscape design often associated with enhancing the experience of living in cities [3,4]. While urbanization, and cities more generally, pose significant challenges to biodiversity and ecosystem functionality, vegetated urban landscapes can provide a range of benefits in relation to human livelihoods and enhance quality of life through urban ecosystem services [5]. Urban ecosystem services are the subset of ecological functions (physical, chemical, and biological processes) that are directly relevant or beneficial to human well-being; the “services” are the assets derived from the functional attributes of ecological communities [5].

The relationship between urban forest structure (inherent characteristics and physical qualities of urban tree populations, see [6,7]) and function (the ways in which structure influences ecological processes, which in turn affects environmental quality and the ability of urban trees to provide beneficial functions, see [6]) was empirically illustrated through the 1990s. Early into the 2000s, the rapidly evolving scholarship on tree-based ecosystem services touted that the urban forest can provide energy conservation, carbon storage,

reduced stormwater runoff, improved air quality, and enhanced human health and well-being (for example [8]). This body of evidence provided swift justification for the initiation of large-scale urban tree planting initiatives [9–11], some of which were systematically researched to assess the range of benefits and costs (or value) embedded in tree survival and mortality [12–14].

Street trees remain a prominent component of urban tree planting initiatives [15–19]. In the United States, for example, street trees constitute over half of all trees installed during many urban tree planting initiatives, with some programs limiting installations exclusively to city streets [20]. Ascertaining the actual benefits and values derived over the course of a street trees' lifespan, however, is complex and nuanced.

Exotic pests [21], pollution and road salts [22,23], and limited spacing [24] are important factors related to streetscapes that can undermine healthy growth and vigor of urban street trees. There may also be unintended consequences of street tree plantings related to air quality and asthma [25], increased nighttime temperatures [26], and unanticipated management costs [27]. These factors may, independently or in concert, undermine the ability of trees to generate benefits. Additionally, the planning, design, and management of streets and their trees often cross several administrative units, including levels of government [28] or internal departments of public works, transportation, parks and recreation, and planning [9,15] that may have differing programmatic priorities.

Nonetheless, the use of trees as a functional, standardized component of urban infrastructure runs parallel to a larger global trend to “infrastructuralize nature” [29,30], even though efforts to measure the actual performance of green infrastructure are still ongoing [31]. The increased desire to generalize tree planting programs as a biotechnological tool [10] or as a nature-based solution [32] warrants closer articulation of the indicators of urban ecosystem services (or disservices) of urban street trees. Identifying the linked or bundled indicators of urban street tree performance can help track driving social–ecological forces as well as pressures on ecosystems [5].

The distribution and demand of existing, urban ecosystem services are not often evaluated together [5], and there is clear importance to not only identify the services (and cited indicators) provided by urban trees but to also understand social-cultural needs for services and identify locations where needs may be unmet. Visibility of this need is growing with increased public attention being directed towards environmental justice theory and practice. Urban neighborhoods and streets are generally seen as privileged by the presence of trees and disadvantaged by their absence [33], and there tends to be an uneven distribution of urban tree canopy cover across ethnic/racial/low SES minority communities [34,35], limiting the amount and quality of ecosystem services provided to these individuals [36]. Even where there is a need to expand tree canopy cover, residents' resistance to street-tree planting programs can be driven by negative past experiences [37] or feelings of exclusion during decision making processes [18].

A systematic literature review—specifically focused on street trees as a distinct facet of the urban forest is one way to begin evaluating the connections between the distribution and demand for urban street trees, as well as geographic and contextual differences in cities across the world [38,39]. No identifiable literature review has collated research on the structure, function, and value of urban street trees, though several reviews have linked street trees and heat mitigation [40], traffic safety [41], and human health-related ecosystem services [42,43].

The aims of this literature review were to identify the scope of street tree literature across academic disciplines (by literature database and journal subject matter), to identify where (geographically) and when (by year) this research was published, and to call attention to discrete, yet inevitably overlapping, street tree research topics in recent decades. A cohesive, cross-disciplinary investigation is valuable to multiple academic disciplines and areas of practice, as urban street trees may serve a range of goals and present distinct challenges that differ from other elements of the urban forest, such as trees in city parks or private residential yards. Additionally, both large-scale greening initiatives and

existing urban forestry programs may require new forms of governance that account for a range of stakeholder attitudes and foster greater institutional capacity than conventional management of urban landscapes [9,28,44–46].

## 2. Materials and Methods

### 2.1. Record Identification

Several published literature reviews from the disciplines of urban forestry and urban greening [47–49] and affiliated social sciences [50–54] were influential in the development of the methodology for this paper. We searched for articles in multidisciplinary (n = 4) and discipline-specific (n = 5) databases covering: all-subjects (Web of Science, JSTOR, Science Direct, MDPI Open Access), biological and environmental sciences (BioOne), human health and behavioral sciences (PubMed Central, PsychINFO), engineering studies (Engineering Village) and one journal-specific database (Arboriculture and Urban Forestry).

This review narrowed articles specifically to street trees, or the trees located in sidewalk cut-outs, street-side planting strips, public-rights-of-way and medians [6] and did not explicitly seek to include articles pertaining to other urban trees (like park trees, residential trees, or woodland trees) or other plant communities (like shrubs, herbaceous plants, and mosses) that comprise an urban forest [55].

In support of this aim, a prescribed set of terms was searched in each database: “street tree”; “sidewalk tree”; “shade tree” AND street\*; “urban” AND “right of way” AND “tree”. When possible, the advanced search setting was used to filter the search terms through the title, abstract or the author-specified keywords. When part of a database’s query algorithm, the Boolean operator “AND” was used between keywords, such as “shade tree” AND street\*, and we used quotation marks (“ ”) to search phrases containing two or more terms (e.g., “shade tree”, not “shade” AND “tree”). The wildcard asterisk (\*) was also used when available to identify plural phrases of the keywords.

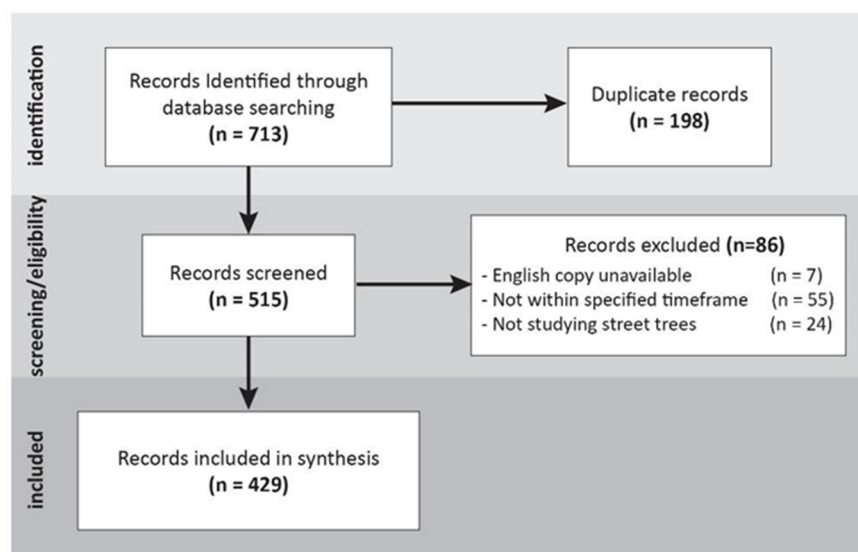
A precedential article was published in 1997 [7] that has served as a benchmark in relation to mapping the trajectory of street tree scholarship over time. Additionally, the 1997–mid 2020 date range corresponds to the “digital age”, and the year 1997 ensures that searches are replicable between archives [54], through to the point at which disrupted patterns of publications ensued due to the onset of the COVID-19 pandemic. Additionally, our search criteria only considered original, peer-reviewed research articles. Books and “grey literature” (e.g., organizational reports, newspapers) were excluded from this re-view. Only English-language articles were considered.

### 2.2. Record Screening and Eligibility

After identifying the initial collection of articles, duplicate records were removed, and the remainder were screened by title and abstract to ensure that the record directly addressed urban street trees. Articles were excluded if the main text was not written in English, was unavailable through the primary authors’ institution library or interlibrary loan or was outside of the desired publication time frame. This record screening and eligibility process is documented in a PRISMA flow diagram (Figure 1 [56]). A total of 429 records were included in this literature review.

### 2.3. Record Coding

The final sample of records was systematically assessed across several classification categories. First, descriptive information for each record was noted to outline the publishing journal, date, and geographic attributes of the research study area. Next, each record was assessed for its dominant research theme, based on the inferred focal topic of study, and then assigned to one of several deductive (a priori) review dimensions, modeled on the framework of structure-function-value [7].



**Figure 1.** Flow chart outlining the literature databases searched and the article screening, eligibility, and inclusion processes.

From this initial coding process, a number of additional thematic sub-patterns emerged, and a second phase of coding was undertaken; these inductive (a posteriori) themes were intended to more specifically illustrate the patterns of “research themes” and “research topics” emergent from contemporary street tree literature. Table 1 was created to outline the operating definitions and examples (from related literature), emergent themes and key challenges identified by the authors from the review process. All authors of this review participated in either the creation of coding categories or an interrater assessment of assigned codes in order to generate consensus and mutually agreed upon classifications across the entire sample of records.

**Table 1.** Review sections and operating definitions/examples used to assess records of this literature review.

Dimension	Research Theme	Research Topic	Emergent Subtopics	Emergent Challenges— Opportunities for Future Research
<i>Structure</i> Inherent characteristics and physical qualities of urban tree populations, largely encompassed by spatial location (including distribution or spatial arrangement and density or aggregate arrangement in relation to other trees or objects), as well as physiological features (species diversity, size or age, condition) [6,7].	<i>Street tree populations</i> the amount, distribution, and composition of leaf area over street and sidewalk surfaces [57]	tree inventory methods	satellite-supported; airplane-supported; on-the-ground photography/scanning; field inventory	digital divide between locales
		establishment and growth	soil amendments; leaf-gas exchange; post-transplant growth	coupled biophysical and human factors
		survival and mortality	longevity; rates over time	coupled biophysical and human factors
		disease/pest management	first reports; impact evaluations	efficacy of nonchemical pest control
<i>Function</i> Manners in which structure influences ecological processes, which in turn affects environmental quality and the ability of urban trees to provide beneficial functions [7].	<i>Supporting ecosystem functions/services</i> the services necessary for the production of all other ecosystem services [58].	biodiversity	species density, distribution, composition, diversity	species diversity, risks of large-scale devastation
		habitat formation	avian and arthropod populations	richness and abundance of organisms reliant on street trees
		nitrogen and carbon cycles	nutrient production and cycling	limited research

Table 1. Cont.

Dimension	Research Theme	Research Topic	Emergent Subtopics	Emergent Challenges— Opportunities for Future Research	
<i>Value</i> Benefits and costs derived from the urban forest (McPherson et al. 1997)	<i>Regulating ecosystem functions/services</i> the benefits people obtain from the regulation of ecosystem processes [58]	air quality	particulate matter; volatile organic compounds; ozone; carbon monoxide; human health outcomes	urban form; planting pattern; air flow	
		carbon sequestration	biomass estimates	loss, release, and net carbon sequestration	
		cooling	human thermal comfort; air/surface temperature; shading; evapotranspiration	urban form; context	
		stormwater management	pit/filter design; infiltration/water quantity and quality	species suitability/structure; impacts on health and growth	
	<i>Provisioning ecosystem functions/services</i> the products obtained from ecosystems [58]	edible food/fruit	pharmaceutical and nutritional benefit	limited research	
		construction material	pruning waste		
	<i>Cultural ecosystem functions/services</i> the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and esthetic experiences [58]	whole-body health outcomes	hypertension; depression; well-being; quality of life; birth outcomes	individual and geographic variation	
		safety	vehicle crashes; crime; wayfinding		
		physical activity	walking; cycling		
		social contact	social cohesion; resident satisfaction		
		cobenefits	any combination of provisioning, regulating, and cultural functions/services		
	<i>Economic valuation</i> monetary expressions of value in terms of assets, costs, and capital investment [59]	economic evaluation	cost–benefit; cost effectiveness; property/rent values	modeling costs/benefits	
		finance administration	projections of workforce and financial demands	limited research, budgeting within a system designed for grey infrastructure	
		<i>Social values and governance</i> nonmonetary expressions of value in terms of norms of law, public interest, or other social processes [60]	policy/planning paradigms	management actor perspectives; planning and policy frameworks; preservation policy	participatory planning processes
			public interest	tree care by private individuals and groups; willingness to pay; tree preferences	procedural justice
	environmental (in)justice	distributional justice; recognition justice	optimize benefits alongside systemic biases		

### 3. Results

#### 3.1. Publication Journal

The top publisher of street tree scholarship between 1997 and December 2020 was Urban Forestry & Urban Greening (n = 108) (Table 2). Other journals commonly found publishing street tree research included Arboriculture & Urban Forestry (n = 47), Landscape and Urban Planning (n = 43), and the presently-retired Journal of Arboriculture (n = 25). The remaining 51% of records were published across 110 separate journals, each holding 1 to 10 records of the sample and covering an array of disciplines, such as: economics (e.g., Ecological Economics), architecture and material sciences (e.g., Building and Environment), health and medical sciences (e.g., American Journal of Preventive Medicine), physics and mathematics (e.g., Nuclear Instruments and Methods in Physics Research A), psychology (e.g., Journal of Behavioral Decision Making), remote sensing (e.g., International Journal of Remote Sensing), and transportation (e.g., Journal of Transport & Health).

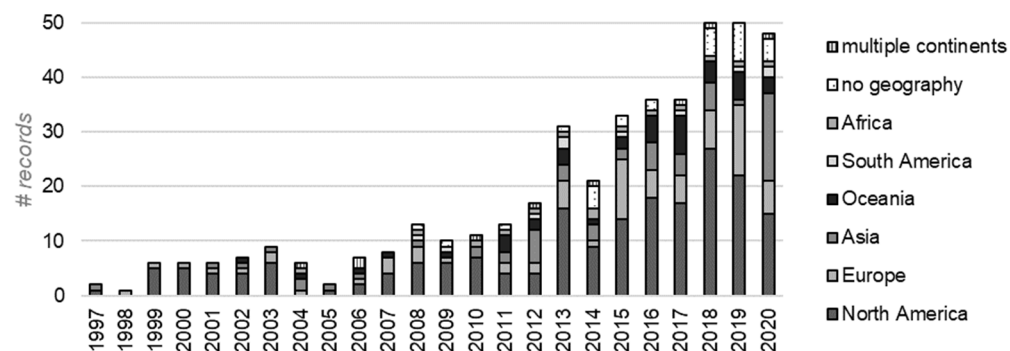
**Table 2.** Activity of top journals publishing street tree research over time.

Journal	No. of Publications			
	1997–2007	2008–2018	2019–2020	Total (n, %)
<i>Urban Forestry &amp; Urban Greening</i>	20	78	10	108, 25.2%
<i>Arboriculture &amp; Urban Forestry</i>	9	36	2	47, 10.9%
<i>Landscape and Urban Planning</i>	2	33	8	43, 10.0%
<i>Journal of Arboriculture</i> *	25	0	0	25, 5.8%
<i>Building and Environment</i>	1	6	3	10, 2.3%

\* Note: The Journal of Arboriculture was retitled Arboriculture & Urban Forestry, January 2006.

### 3.2. Publication Timeline and Study Area Geography

Consistent with other reviews in urban forestry [48,61], the greatest amount of street tree studies over time has taken place in North America (total  $n = 197$ ) (Figure 2)—particularly the United States (total  $n = 166$ ). Research from other continents has been rising in recent years, with a notable increase in Europe and Asia after 2010. While research originating from South America and Africa remains uncommon, publication rates regarding street trees are also increasing from these areas. Nonetheless, many subregions—including Central America and Central Asia—are not represented in this sample. The number of records without a specific geographic setting (“n/a”) has also risen since 2014, perhaps reflecting recent use of computer simulations and high-capacity mathematical modeling as alternate research environments, as well as the globalization and mainstreaming of scholarship pertaining to ecosystem services [10,62].

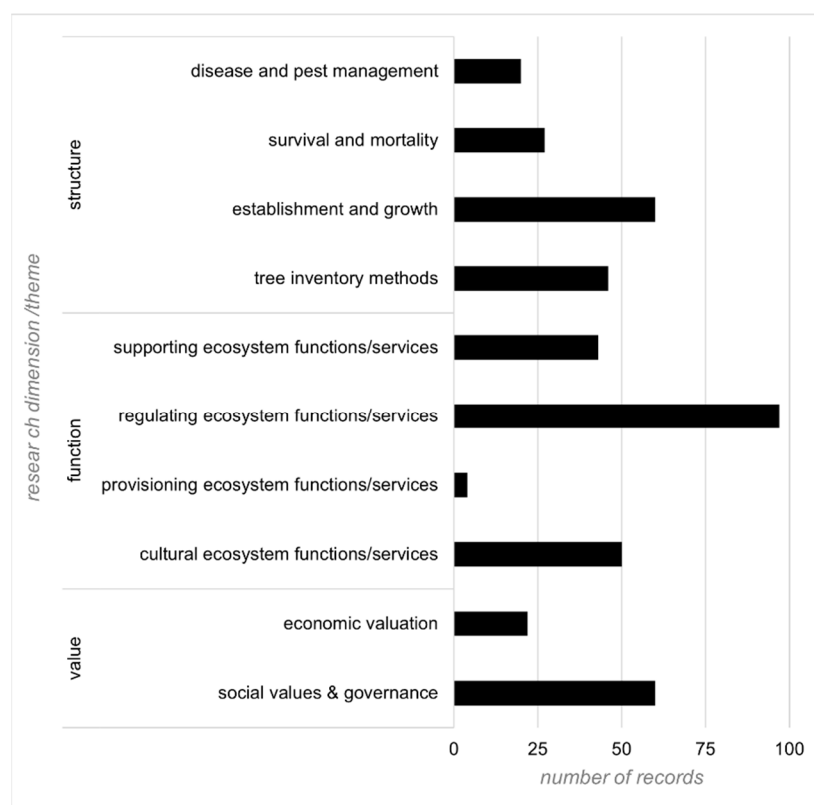


**Figure 2.** Distribution of records over time and by continent. Note: “no geography” refers to records that did not have a physical study area and relied on computer simulations or other digital models.

In spite of the dominance from western countries, a large number of cities and countries have served as settings for street tree research (see Supplementary Materials Table S1 for a more complete list of records). For example, research conducted in Asia has been spread across 39 separate cities in 13 countries, including the Middle East [63] and Southeast Asia [64]. Street tree research from South America also covers 7 cities in 3 countries, namely Chile [65], Argentina [66], and Brazil [67]. In addition, a wide variety of South African cities have been subject to more research ( $n = 30+$ ) compared to the African continent as a whole.

### 3.3. Research Dimensions and Themes

The breakdown of records by thematic focus denotes that street tree research has been weighed toward the “dimensions” of structure and function, particularly measures of street tree establishment and growth and regulating ecosystem functions/services (Figure 3). A noticeable collection of articles focus on cultural ecosystem functions/services while a much smaller subset focused on supporting and provisioning ecosystem function/services. The “dimension” of value holds the smallest set of records.



**Figure 3.** Distribution of records by research dimension and theme/topic.

#### 3.3.1. Structure

*Disease/Pest Management.* A relatively small but noteworthy part of street tree management research applies to disease and pest management ( $n = 20$ ), particularly with studies from North America since 2009 ( $n = 13$ ). Nonetheless, these articles report non-chemical control and treatment for street tree pests and pathogens, like the traditional Japanese moth trap or komo-trap [68], as well as techniques to measure and project the distribution of and susceptibility to pests [69]. Also, a portion of the articles collected in the review were the “first report” of fungal pathogens in a new street tree species or in a new region, for example, in 2009 newly-international pathogens such as the European pear rust (*Gymnosporangium sabinae*) infestation was reported in Farmington, Michigan (U.S.) [70]. The “first reports” are unique in our literature review due to their relative brevity and less recent publication timeline, where the most recent report was published in 2012 [71].

*Survival and Mortality.* In contrast to urban street tree establishment and growth, urban tree survival is defined as the cumulative factors that contribute to the health and longevity of urban trees [72], whereas urban tree mortality factors are those contributing to the death and premature removal of a tree [61]. Of the biophysical factors, taxa, age, and site conditions were most commonly researched [73]. As sources of vulnerability that perpetuate survival and mortality, additional research focused on the effects of lead [74] and salt stress [23], issues related to irrigation or drought [75], and physiological decay [76]. In relation to urban street trees, the exploration of human factors have been sparse but

meaningful subjects of the survival/mortality research, covering the role of vandalism [77] and tree preservation programs [78] on street tree survival. Most of these studies were published from North American research since 2009, but earlier research from Europe and later research from Asia also exists.

*Establishment and Growth.* Research of street tree establishment and growth has been conducted fairly consistently over time and across the world, with exception to studies Africa and South America that were not seen in our sample. Indicators of street tree health and growth have been subject to different assessment processes via cultivar performance over time (e.g., Japanese tree li-lac (*Syringa reticulata*), [79,80]; Serviceberry (*Amelanchier* spp.), [81,82]), leaf-gas exchange [83], biomass production [84]. Other research isolated specific biophysical contributors to establishment and growth, such as overall site conditions [22], pavement material [85], soil compaction [86], aeration [87], and different forms of soil amendments like biochar [88], compost [89], or engineered soils [90]. Additionally, the persistence of certain hydro-logic conditions, like water retention [91] or drought [92], as well as the presence of fungal colonies [93] have been subject to research.

*Tree Inventory Methods.* Street tree inventory methods have been used to aggregate the spatial location of individual or collections of trees, above or below-ground components of the trees, or the overall “greenness” of a street. Similar to [94], results from our review cluster street tree inventory methods as: aerial approaches (satellite- and airplane-supported methods), on-the-ground scanning or digital photography, and field surveys (Table 3). Several records combined inventory methods, together using the outputs of satellite imagery with airplane support-ed methods [95] or satellite imagery and on-the-ground photography [96]. Other records validated or refined allometric modeling equations to predict the diameter, height, or crown width of a street tree population from a smaller subset of data [97].

**Table 3.** Summary of records across street tree inventory methods. Full listing available in Supplementary Materials.

<i>Inventory Method</i>	<i>Definition (Based on Nielsen et al. 2014 [94])</i>	<i>Inventory Description</i>
Satellite-supported inventory method	use of scanners or cameras to collect information from large areas via satellite	Landsat ETM+ and Quickbird (Small et al. 2006), Landsat-9 and MODIS [98–101]
Airplane-supported inventory method	use of scanners or cameras to collect information from large areas via airplane	airborne LIDAR; airborne laser scanning [102–104]
On-the-ground scanning/photography	covers smaller areas of a single tree or small patch of trees); is more time consuming, yet offers a much richer scale of detail and precision than is permissible using high-resolution imagery	Google Street View; mobile laser scanning; terrestrial laser scanning; extracting mobile LiDAR point clouds [105–118]
Field survey	based on both the measurements and/or inspection of individual trees; while labor-intensive and time-consuming, this method can speak directly to the predictors or confounders of local conditions (human or biophysical) that impact street tree structure, function, value, and management regimes	led by volunteer participants or citizen scientists; documenting multi-stem DBH; documenting host trees for invasive insects across re-gional urban forests; documenting street tree composition of industrial land uses, or land used for manufacturing, public utilities, warehouses, or similar commercial operations; documenting post-storm damage to urban trees [119–125]

### 3.3.2. Function

*Supporting ecosystem functions/services.* Research on street tree species diversity and supporting habitat was reported from North America and Oceania as early as 1999 and only by 2012 was research reported from other global continents. Species diversity inventories have noted tree health or vigor [126], species change over time [127], and distinctions between native and non-native tree species [128]. Street tree diversity is cited as a key management indicator to monitor vulnerabilities, like pest invasion [129] and local areal homogenization [130]. Several records have also studied street tree diversity as key to enhancing local habitat for urban avifauna in several countries, including South Africa, China, Japan, Brazil, and the U.S. [131], and arthropod populations in the U.S. [132]. As a separate form of supporting ecosystem function, one article researched the nitrogen and carbon cycling capacity of street trees, comparing differences based on street traffic density and neighborhood income level in California, U.S. [133].

*Regulating ecosystem functions/services.* The largest collection of records identified in this review explored the regulating ecosystem functions/services of street trees and focused on impacts related to cooling (n = 51), air quality (n = 20), stormwater management (n = 16), and carbon sequestration (n = 9).

The cooling properties of street trees have been assessed through different variables, approaches, and outcomes in cities and countries across the world, and the primary outcome or cooling mechanism under investigation addresses thermal comfort, air/surface temperature, shading, and evapotranspiration (Table 4). Studies about cooling are largely reported from Asia (n = 15) and Europe (n = 12) and have been most consistently published since 2009.

Of the air quality articles, seven of the twenty records linking street trees to air quality studied particulate matter [134], defined as the different forms of hazardous particles suspended in air. The remaining records examined street trees' ability to regulate carbon monoxide [135] volatile organic compounds [136], and ozone [137]. The filtering capabilities of street trees were modeled alongside impacts to air flow in a street canyon [138] or impacts from street tree planting patterns [139]. Alternatively, field research examined the airborne pollutant interception capacity of street tree patches and species typical to Medi-terranean regions [140], and the deposition of pollutants on street tree bark in Buenos Aires, Argentina [66]. Together, research about air quality was reported from Europe (n = 7) and to a lesser extent North America (n = 5) and Asia (n = 4).

**Table 4.** Records addressing the cooling function of street trees. (Full listing available in Supplementary Materials).

<i>Cooling Mechanism</i>	<i>Context</i>	<i>Geographic Distribution</i>	<i>Select Citation(s)</i>
Shading	improve building energy efficiency	Manchester (U.K.), Phoenix, Arizona (U.S.)	Skelhom et al. 2016, Wang et al. 2016, Armson et al. 2013
	shade cover in street canyons	Boston, MA (U.S.), Singapore, Hong Kong (China)	Li et al. 2018, Gong et al. 2018, Richards and Edwards 2017
	UV protection for school children	Australia	White et al. 2017
	shade cover for pedestrians	Pécs (Hungary)	Kántor et al. 2018
	improve pavement performance	Modesto, California (U.S.)	McPherson and Muchnick 2005

Table 4. Cont.

<i>Cooling Mechanism</i>	<i>Context</i>	<i>Geographic Distribution</i>	<i>Select Citation(s)</i>
Air/surface temperature	variation among street tree species	Dresden (Germany), Wollongong, New South Wales (Australia)	Aguiar et al. 2014, Gillner et al. 2015, Maando et al. 2019
	variation between vegetation and urban morphology	Manchester (U.K.), Berlin, Cologne (Germany)	Hall et al. 2012, Berger et al. 2017
	variation due to street canyon and planting composition	Tel Aviv (Israel), Gothenburg (Sweden)	Shashua-Bar and Hoffman 2003, Konarska et al. 2016
	variations in microclimate	Tel Aviv (Israel)	Shashua-Bar et al. 2010, Takebayashi et al. 2014
	variation between sidewalks and roadways	n/a	Wang 2014
	variation between street tree size and spacing	Montreal, Quebec (Canada)	Wang et al. 2016
	variation between streets and courtyards	Tel Aviv (Israel)	Shashua-Bar and Hoffman 2004
Evapo-transpiration	variation among growing conditions	Munich (Germany)	Rahman et al. 2013
	variation among planting compositions	Sodegaura (Japan)	Teshirogi et al. 2020
	variations in microclimate	Munich (Germany)	Rahman et al. 2017
	reduce damage to study specimens	Shenzhen (China)	Qiu et al. 2020
Thermal comfort	variation based on combinations of air temperature, mean radiant temperature (MRT), wind speed and direction, short-and long-wave radiation	Saitama Prefecture (Japan), Utrecht (Netherlands), Adelaide (Australia), Melbourne (Australia), Munich (Germany), Xi'an (China), Vancouver, British Columbia (Canada), Salt Lake City, Utah (U.S.), London (U.K.), Harbin (China)	Park 2012, Klemm 2015, Razzaghmanesh 2016, Sanusi 2016, Thom 2016, Park 2018, Rahman 2018, Yang 2018, Aminipouri 2019a, b, Park 2019, Krayenhoff 2020, Li 2020
	calibrate human energy balance	Melbourne (Australia), Heilongjiang (China), Guangdong (China), Bangkok (Thailand)	Morakinyo 2016, Sanusi 2017, Zhao 2017, Zheng 2018, Srivanit 2020
	reduce heat stress	Sao Paulo (Brazil)	Johansson et al. 2013

Street tree pits have been researched to mitigate stormwater at a neighborhood scale [141], and within an urban catchment [142]. Other research considered the stormwater management effectiveness of street tree pits, based on seasonal performance [143], soils [144] and overall management [145]. Most of this research is reported from North America (n = 9).

The ability of street trees to store and sequester carbon has been approximated via biomass estimates [146] or estimated based on the larger context of soils and vegetation [147]. Other records estimated carbon release or transfer, such as soil carbon loss due to root uptake [148], carbon release due to composting or incinerating dead street trees [149],

or net sequestration during lifecycle of a street tree (e.g., carbon release due to tree mortality across a city) [150]. Unlike other domains of research from this sample, interestingly, this small line of research was first reported from Africa in 2009, then grew to Asia, Europe, and North America in years following.

*Provisioning ecosystem functions/services.* Street trees have been sparingly researched as a source of edible foods or novel construction and pharmaceutical products (total  $n = 4$ ). A simulated case study in Perugia, Italy, for example, created tiles made from the pruning waste of linden trees (*Tilia* spp.) as a sustainable alternative to traditional commercial roof insulation [151]. As edible food, the elemental and nutritional value of wild plum (*Harpephyllum caffrum*) street tree seeds in South Africa showed low levels of toxins and relatively high levels of key nutrients such as calcium, magnesium, and iron [152]. Similarly, the potential pharmaceutical uses of the horse chestnut (*Aesculus hippocastanum*) street trees in Vojvodina Province, Serbia were explored for anti-inflammatory properties, and analyses revealed that the nut contained valuable fatty acids and bioflavonoids, such as aescin, which are useful raw materials in the pharmaceutical industry [153]. Forageable woody species near street trees have also been documented in New York City (U.S.) [154].

*Cultural ecosystem functions/services.* Self-reported measures of overall, or whole body, health [155] and quality of life [156] have explored the ways in which access to nature-based public goods, including street trees, improve perceived and physiological health and well-being ( $n = 16$ ). Street trees have also been studied as a tool to “restore capacities” of human health, primarily by way of reducing depression [157], as well as improving other measures of psychological distress [158] and stress recovery [159].

As an element of the physical landscape, street trees have been studied as an aesthetic intervention that create more pleasant conditions for physical activity and active transportation ( $n = 14$ ), including walking [160], cycling [161], or both [162]. Street trees are also presumed to have positive impacts on social contact—or the social interactions or relationships between individuals—by improving the pedestrian environment and, by extension, strengthening residential satisfaction [163] and social capital [164]. Connections to street trees as a safety intervention has also been assessed ( $n = 8$ ), and research has focused on crime [165], traffic crashes [166] and improvements to wayfinding [167].

The co-benefits of street trees have also been explored in several ways ( $n = 7$ ), such as a tool to promote active living and meet sustainability goals [53], as well as the boundless combination of benefits that can improve residents’ quality of life [168]. Together, research of the cultural ecosystem functions/services of street trees is reported from North America ( $n = 24$ ) and more sparingly from Europe ( $n = 10$ ), Asia ( $n = 8$ ), Oceania ( $n = 3$ ), South America ( $n = 2$ ), and Africa ( $n = 1$ ).

### 3.3.3. Value

*Economic valuation.* The economic value of street trees has been measured through the costs of preventative management practices, overall cost-benefit comparisons, or indicators of broader economic impact (total  $n = 19$ ). This line of research was first reported from North America in 1999 but not in Europe until 2010 or Oceania until 2013.

From this research, proactive management practices like biocontrol [169] or strategic pruning [170] have been calculated to assess the return on investment of targeted prevention. The costs of street tree management have also been weighed alongside quantified regulating ecosystem service benefits; these include carbon dioxide removal [171], air pollutant reductions [65], and stormwater abatement [172]. A combination of benefits have also been investigated using individual metrics [57] or the iTree software [173]. The impact of street trees to the broader local economy has been measured through actual property value [174] and willingness to pay higher values for properties near street trees [175].

A small but noteworthy selection of records ( $n = 3$ ) from the U.S. also investigated the fiscal and budgetary requirements of street tree planning and management. In-depth simulations were used to project street tree management demand, including employee schedules and workloads, in the borough of Staten Island, New York (U.S.) [176,177]. A

separate but equally unique record articulated the fiscal challenges of budgeting street tree care in a system designed for ‘grey’ built infrastructure management [29].

*Social values and governance.* The policy and planning paradigms guiding street tree planting and management have explored institutional stakeholder cooperation as well as broader prioritization frameworks, although research from North American systems dominate since the early 2000s (n = 28) compared to all other parts of the world. Several records compared institutional stakeholder perspectives, including municipal officials, non-governmental organizations [10], private sector utility arborists [178], and construction developers [179]. Other records described the institutional opportunities and barriers to effective urban tree management in Africa, Europe, and North America or transnational differences in urban forestry practices and knowledge [180,181].

In terms of planning frameworks and processes, some records evaluated street-level planting criteria, such as site selection [182] and tree species selection [183], while others deliberated upon the role of street trees as part of broader heat mitigation strategies [184] or scenario planning [185]. Another set of records describe circumstantial implications of street tree planning and policy for specific populations in specific places, such as reforestation Tokyo and Hiroshima, Japan after World War II [186] and street vendors’ use of street trees in Hyderabad, India [187].

A number of articles explored the motivations and conditions by which individuals or community groups demonstrate public interest or preferences for street trees and stewardship (n = 25). Stated preferences, or measured value statements of preferences from participant residents [188] and urban forest managers [17], were also prevalent. Other studies were conducted through interviews with specific communities or neighborhoods, exploring topics of tree care experience [189], government versus private maintenance [16], tree loss due to invasive pests [190] or unprompted, self-initiated management [191]. Other records explored different approaches to connect residents to street tree stewardship, comparing active face-to-face outreach to passive outreach methods like mailers or postcards [192,193].

Equity appears to be a recent cross-continental topic of research (n = 14), where all records in this category have been published since 2010 in Africa, Asia, Europe, North America and Oceania. Alongside the spatial presence and density of street tree distribution [194], other research also considered the inequitable distribution of street tree species diversity [195] as well as the oft-neglected dimension of recognition justice (i.e., consideration of the knowledge and norms of residents affected by distributional injustices) [196]. Emergent from this review, Watkins and Gerrish [35] report a meta-analysis of such studies and consider the research to be inconsistent across research design, methodologies, and study areas; however, the authors do conclude that race-based inequities in street tree abundance do exist within many cities.

## 4. Discussion

### 4.1. *The Multidimensionality of Urban Street Trees*

From this research, street trees are distinguished as a multidimensional feature of an urban forest, or through characteristics that can be articulated by discrete (and often overlapping) social, spatial, functional, and contextual dimensions.

Street trees are considered an idealized element of city planning models [197], and the social merit of street trees has been identified in this review from its meteoric increase in publication volume as well as its breadth of disciplinary focus. Approximately half of the literature sample that we identified was published in only a few urban forestry journals, with the remaining half being published across 110 independent, cross-disciplinary journals. The volume and range of research examining street trees highlight not only their aesthetic and experiential values for urban residents, but also their role as a component of green infrastructure by urban forestry managers and the broader public.

By including cross-disciplinary databases related to human health and behavioral sciences (PubMed Central, PsychINFO), this review also emphasizes that street trees can be an important form of nature contact for city residents. Nature contact, or the ways

in which exposure to nature affects human health and well-being, varies by spatial scale, proximity, sensory pathway (visual, auditory, etc.), or the individual's activities and level of awareness while in a natural setting [198]; an in an era where this is wide consensus that all residents should have access to trees and greenspace, street-side tree plantings are one way to bring these benefits into the lived experience of more people [199]. In terms of the physical qualities of urban street tree populations, this review identified that there is a widespread, baseline interest in assessing street trees as a component of the urban forest. Not surprisingly, our review anecdotally found that street trees are studied at the scale of individual trees, groups of street trees, a single tree amongst a matrix of other tree planting locations, or as a discrete component across an urban forest. This literature review did not assess the ways in which the position or placement of street trees is related to other planting locations in cities, however this is a worthwhile inquiry for future literature reviews or empirical research.

Nonetheless, urban tree inventories are a popular way of engaging community members and quantifying street trees, however, important barriers include access to and knowledge of various concepts, for example geographic information systems and species or cultivar identification. Important research contributions have also been made relative to urban street tree growth and longevity (i.e., phases commencing with tree establishment, through to tree mortality), informing professionals and residents about the overall difficulties to grow trees in urban roadsides. Further place-specific exploration is needed, however, to detail how trees respond to the many nuances of growing in an urban environment including the effects of soil availability/quality, and presence and proximity of grey infrastructure. Formal longitudinal study of urban tree mortality should also be expanded as many of the ecosystem services derived from urban trees are directly related to tree maturity and persistence over time.

When reporting the functional dimensions of street trees, regulating ecosystem services are, by far, the most abundant theme of research, followed by studies of valuation. Since our record search started only in 1997 (on the cusp of the “digital age”), it is unclear if this trend has persisted since the beginning of scholarly publications about street trees. Nonetheless, the idea of ascribing a dollar-amount, or economic value, to the function of trees and disseminating publicly accessible, user-friendly digital tools to measure such attributes (e.g., iTree), may explain the expansion of research on regulating ecosystem functions in the mid-to late-2000s. Notwithstanding critiques of the urban ecosystem services framework [62,200], the ability to quantify and monetarily value ecosystem services has helped decision makers to mobilize political and financial resources to support urban tree planting initiatives, and in some cases, to refocuses urban trees as a mere cost and potential liability, to also framing them as a value and investment [201]. Budgetary constraints do, nevertheless, continue to be prominent in the literature as a barrier to urban forest management at the local level and further investigation of this topic is timely.

Though digital decision support tools may assist in the selection of tree species and the identification of planting locations for a given ecosystem service, they cannot readily account for the personal values that may be present (or absent) in management decision making. So while a robust literature on the structural and functional attributes of street trees does exist and provides a valuable baseline of knowledge, on its own this information cannot provide the most inclusive picture of the human dimensions of management decision making and support. In essence, not all urban forest stakeholders will hold positive opinions about street trees [27,37] and the diversity of individual beliefs, attitudes, and preferences behind these reasons must be investigated with more clarity [202]. This is especially important in light of the increasingly urban settlement pattern of people worldwide [203] and corresponding interest in urban greening and tree planting initiatives [20,204].

#### 4.2. Limitations

The methodology and results of this literature review are not without limitation. First, the purpose of this review was to address the multidimensional nature of contemporary urban street tree scholarship. We did not seek to assess the strength of evidence or methodological rigor between records, as each ‘research theme’ and ‘research topic’ is supported by one or more complementary but distinct literatures. However, from our assessment of this particular sample, the research was often clearly based on disciplinary orientation toward the biophysical environment (e.g., climate zone, ecological disturbance), economic valuation (e.g., econometrics), human geography (e.g., physical urban form, political will), and human psychology (e.g., experiential or mental models). Since these assumptions are not only relative to the type of science being conducted, but also to the biophysical and social context of the research, we believe a more deliberate meta-analysis of particular scales and scopes of interest will be a valuable asset to generalize research about street tree structure, function, and value.

Second, our approach to selectively include discipline-specific databases inevitably excluded relevant journals and records. For example, our methodology did not capture the Taylor & Francis journal *Arboricultural Journal*. Taylor & Francis does index their journal archive as part of one database we included for this review (PubMed Central); however, the specific journal *Arboricultural Journal* is not a part of PubMed Central’s journal list [205] but may have appeared in databases excluded from this review (e.g., Scopus, Google Scholar) [206]. While the goal of our literature review was not to compile a census, or full collection, records of interest or importance may have been unintentionally excluded from the reported results and synthesis.

Third, the sample of records reported in this review is limited by our search criteria, namely publication date, peer-reviewed scholarship, English-language publications, and database entry fee. Given the legacy of arboriculture and urban forestry scholarship prior to 1997 as well as the abundance of information available in the grey literature (e.g., digital magazines, technical reports), our review only represents the scholarly literature captured in our search. For example, several non-English records emerged and were not included. Similarly, many of the records reviewed in this paper are freely accessible through open-source journals, while remaining articles are locked behind paid-access databases.

Lastly, our approach to retrieve the final sample of literature could have been expanded and streamlined by automation technologies. Innovations in computer science and information technology (e.g., machine learning, data extraction) can expedite the time and resources needed to search sensitive keyword and database combinations, while minimizing human-induced biases, costs, and time [207]. Future reviews would benefit from consulting a computer programmer or information technology technician early in the data collection process to better refine an automated data collection process.

#### 5. Conclusions

The goal of this systematic literature review was to report on the scope of street tree literature across academic disciplines, to identify where and when this research was published, and to call attention to discrete, yet inevitably overlapping, street tree research topics in recent decades.

Of the 429 records collected as part of this review, approximately half were identified across three primary scholarly journals in urban forestry, with the remainder being distributed across 110 cross-disciplinary journals. An exponential rise in the number of articles published between 1997 and 2020 reflects similar growth in scholarship pertaining to urban tree planting initiatives [20]. Urban tree/forest management research from Western countries continues to disproportionately inform our understanding of street trees; new directions of research from other global regions are on the rise and are necessary to inform emerging scholarship on a variety of topics, including place-specific human health outcomes, ecosystem functions, services, and disservices.

The potential for street trees to regulate specific ecosystem functions (e.g., cooling) has been subject to the greatest attention in this sample and has been studied through various mechanisms (e.g., shading, evapotranspiration, thermal comfort) and site conditions—creating a large, yet highly context-specific pool of literature. Similarly, the cultural ecosystem services of urban street trees are studied as an important form of nature contact through a range of pathways (e.g., physical activity, stress reduction) and health/well-being outcomes (e.g., safety, obesity, birth outcomes)—again, creating a sizable body of literature with results relative to individual and geographic variation.

The dimension of value and its research themes addressing environmental (in)justices are on the rise, though most of the focus appears to relate to distributional justice, with less of an emphasis pertaining to procedural or recognition justice. Though opportunities for future research abound and may include meta-analyses led by discipline-specific, subject-area experts, the breadth of scholarly research and discourse on urban street tree structure, function, and value will no doubt continue its ascent for years to come.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f13111779/s1>, Table S1: STREET TREE STRUCTURE.

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