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Review

# A review of urban forest modeling: Implications for management and future research

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ABSTRACT

Urban forest modeling is becoming increasingly complex, global, and transdisciplinary. Increased modeling of urban forest structure and function presents an urgent need for comparative studies to assess the similarities and differences between modeling techniques and applications. This paper provides a systematic review of 242 journal papers over the past two-decades, and identifies 476 case studies. We assess model case studies among different locations, units and scales, compare the ability and functional capacity of the models and different tools, compare papers published in different disciplines, and identify new emerging topics in the field of urban forest modeling. Conclusions from this analysis include: (1) the spatial distribution of case studies is primarily clustered around the US, Europe, and China, with the most popular units to model being streets and parks; (2) the most commonly used model types are the i-Tree toolset, ENVI-met, computational fluid dynamic models, and the Hedonic price model; (3) uncertainty assessment of urban forest models is limited; (4) spatially explicit models are critically important for estimating of ecosystem services as well as for environment management; (5) most case studies focus on biophysical benefits with few studies estimating economic and social benefits; and (6) linkages between urban forests and their social-psychological and health effects are less common due to subjectivity and uncertainty in expressing and quantifying human cultures, attitudes and behaviors. Based on a comparison of different models and a syntheses of case studies, we make suggestions for future research connecting urban forestry and urban ecosystems, model development, and ecosystem services. Such knowledge is critical for policy- and decision-makers, and can help improve urban forest planning, design and management.

## 1. Introduction

A term first used in 1965 (Gerhold, 2007), “urban forestry” has become increasingly transdisciplinary in terms of theories (from both physical and social sciences), methods (e.g., Geographic Information Systems, remote sensing, monitoring, and modeling), and participants (e.g., researchers, government officials, citizens, and volunteers). Many definitions of urban forestry have been given, and the definition and terminology harmonization is challenging (Konijnendijk et al., 2006). However, several widely-used definitions, such as those provided by Jorgensen (1986), Society of American Foresters (Helms, 1998), Konijnendijk et al. (2006), and Nowak et al. (2010), all emphasize urban forestry’s comprehensive nature, which involves scientific, management, and planning elements. In this article, we look at urban forestry in a general way. Literally, “urban forestry” consists of two parts “urban” and “forestry”. An “urban” system is a spatially heterogeneous, complex adaptive social-ecological system (Wu, 2014), which aims for not only environmental functionality, but also social equity and economic viability (BES LTER, 2018). Compared to traditional forestry, “forestry” in the urban context focuses on additional services to advance urban sustainability. As a demographic trend and land transformation process (Pickett et al., 2001), urbanization creates many environmental issues (e.g., Duh et al., 2008; Grimmond, 2007; Poumanyvong and Kaneko, 2010); these issues make the design of sustainable urban forestry (Fazio, 2003) particularly challenging.

The morphological characteristics (e.g., leaf area, stem diameter), functions (e.g., photosynthesis, evapotranspiration), and structure (e.g., species composition, spatial pattern) of trees provide a wide range of ecosystem services (ES) and benefits that can alleviate the adverse effects of urbanization (Nowak and Dwyer, 2007). Many cities have established substantial programs to increase their tree canopy coverage (Morani et al., 2011; McPherson et al., 2011). However, simply

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increasing tree canopy itself does not guarantee the provision of expected ES. For example, Vos et al. (2013) have shown that it may not be a viable solution to alleviate a local air pollution hotspot by using urban vegetation, and Wu (2014) indicated that urban greening may lead to unintended environmental injustice issues such as 'ecological gentrification'.

To better manage urban forests and maximize tree benefits, several models have been developed and implemented. These models have been applied in case studies on individual locations and provide us with knowledge about urban tree services and benefits. Although there is evidence of a global trend of increased urban landscapes and ecological structural homogenization (Wu, 2014; Turner and Gardner, 2015), each city is still unique, and the ES provided by urban forests change with forest characteristics and environmental conditions. Findings for one city can be quite different compared to those of another city, and the current global distribution of urban forest case studies tends to cluster within specific regions.

There are limited comparative studies of urban forest ecosystem models. Of interest here is summarizing and generalizing findings across a wide range of case studies to identify trends and gaps in urban forest modeling. Such knowledge is critical for urban forests research and management. By reviewing urban forest modeling over the past two-decades, the goal of this paper is to facilitate a better understanding of model characteristics and uses, and integrate different model practices and case studies to advance our knowledge of urban forestry and inform future research and management.

## 2. Key terms and concepts

The urban forest contains all trees, shrubs, lawns, and pervious soils in urban areas (Escobedo et al., 2011; Roy et al., 2012). Our review here focuses on trees and shrubs in different urban areas (e.g., street, park, and residential area), as well as their local site and environmental conditions. Green roofs, green infrastructure, and green space (Rowe, 2011) are all different, but related concepts, and they include various vegetative components. They are also included in this review if their study focuses on the structure and benefits of urban trees and shrubs.

There are many definitions of interdisciplinarity and transdisciplinary. We differentiate them based on participants and final goals. Here interdisciplinary studies refer to the involvement of several academic disciplines under a common research goal to create new knowledge. Alternatively, transdisciplinary studies involve not only academic researchers but also non-academic participants (e.g., the public and policy-makers) for the purpose of solving real-world problems (Tress et al., 2005).

A model is a simplified description of a real system with inputs, key components of the system and their relationships, and outputs constrained within specific spatial boundary (Jones, 2013). A model can be developed based on either mechanistic approaches or empirical relationships, or a hybrid of both. The models considered in this study must be able to describe urban forest structure (e.g., size, species composition, spatial configuration) (Nowak et al., 2008), and function (e.g., various ES) in highly complex systems. They use forest structure, as well as other site and environmental parameters, as input variables to estimate ES as model outputs. We focus on numerical and statistical models since they are used extensively to quantify forest derived ES. To link more directly to management implications and limit the scope of the analyses reviewed, models focusing entirely on forest structure and dynamics (e.g., growth, mortality) are excluded. As input datasets are a necessary part of any model, characteristics of input datasets are also explored from the perspective of data acquisition approaches: bottom-up approaches mainly consist of field surveys and sampling while top-down approaches rely mainly on remotely sensed data.

Since the release of the UN's Millennium Ecosystem Assessment (MEA) (MEA, 2005) and The Economics of Ecosystems and Biodiversity (TEEB) report (TEEB Foundations, 2010), ES have gained broader attention in the literature (Escobedo et al., 2011; Gómez-Baggethun and Barton, 2013). The differentiation between ecosystem function and service has been well-established, with the former emphasizing ecosystem processes (means) while the latter focusing on specific outputs or products (ends) (Escobedo et al., 2011; Roy et al., 2012). In this study, we focus on ES that can be derived from forest structure and function. Following the classification scheme of urban forest ES provided by Nowak and Dwyer (2007), we expressed them in three value-domains: biophysical, social and economic.

## 3. Study methods

Model practices and case studies of urban forests in academic English-language journals were reviewed during the past two-decades (1996–2017). Here we use the term "case study" to refer to one simulation at one location employing either numerical or statistical models. To be comprehensive, objective and accurate, a systematic quantitative literature review was first performed (Petticrew, 2001). Two worldwide scholarly electronic databases, Google Scholar and Scopus, were employed in this study. Keywords or combination of keywords used for the search included: 'urban tree/forest/vegetation/green roof', 'ecosystem services/benefits', and 'model/tool'. For each identified paper, articles of related or similar topics were identified via: (1) references within the paper, (2) 'related articles/documents' function in Google Scholar and Scopus, and (3) articles that cited the paper. Although this step was mainly implemented based on Google Scholar and Scopus, other scholarly electronic databases were involved because search results often led to different links (e.g., Science Direct, Research Gate, Springer Link, and individual journal websites). While our literature search was not exhaustive, we believe we've captured a majority of journal articles on this topic.

After identifying journal articles, the following items were extracted from each paper: (i) year of publication, (ii) case study location, (iii) model(s), (iv) input data, (v) title, (vi) author(s), (vii) journal, (viii) discipline, and (ix) topics and ES. A spatio-temporal analysis was then performed using (i) year of publication and (ii) case study location. For this analysis, each paper was grouped by continent and major climatic zone to determine the distribution and pattern of urban forest studies. Following the work of Roy et al. (2012), the continents included were North America, South America, Europe, Asia, Australia, and Africa; and the climatic zones were tropical, dry, subtropical, temperate, and continental. Other space-based analyses included identifying the scale of each study performed (e.g., city, region, nation), and the unit for each case study (e.g., park, street, neighborhood, community, district, watershed). Next, comparisons among models and among disciplines were conducted using (iii) model(s), (iv) input data, and (viii) discipline. For each model, the total numbers of papers and citations (how many times that particular paper has been cited) were calculated. In addition, as input datasets are part of any model, each paper was also characterized based on the acquisition sources of the input datasets. Each journal was grouped into a specific field, and a comparison among fields was conducted. We grouped journals into fields based on journal description and the topics of the identified papers from journals. Finally, comparisons between ES were investigated using (ix) ES topics.

## 4. Results

We identified 242 relevant papers and 476 case studies over the time period 1996–2017 (see Supplementary Material for a list of papers), with more than half of the papers published during the past 6 years (2012–2017). There are more case studies than publications because some papers include several case studies. Citation numbers, primarily conducted between the period of November 2017 to January 2018 based on Google scholar, show a relatively exponential-type growth pattern over time (Fig. 1), reflecting the increasing number of publications, activities and influences of this field.

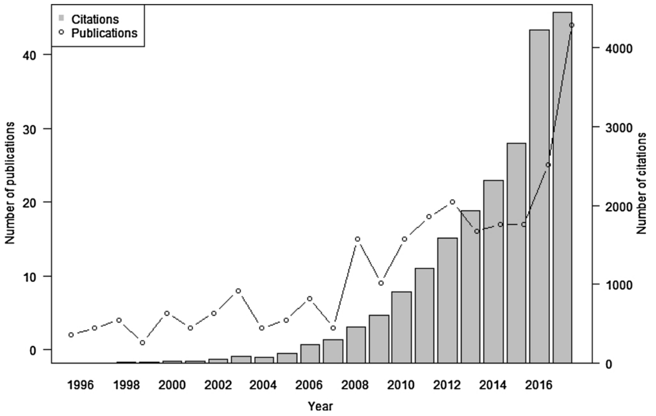

**Fig. 1.** The number of publications and citations yearly from 1996 to 2017 (citation counting was conducted between the period of November 2017 to January 2018 based on Google scholar).

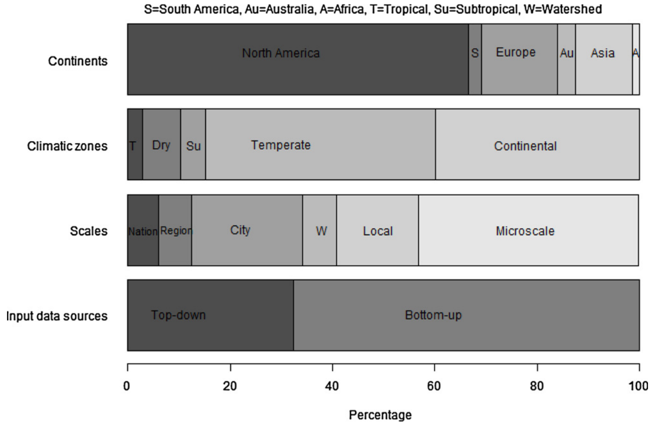

**Fig. 3.** Summary statistics (percentage) of 242 original papers in different sub-categories: continents, climatic zones, scale, and input data sources. The percentages for each continent and climatic zone are calculated based on number of case studies, while percentages for each scale and input data source are based on number of papers.

### 4.1. Place-based, comparative studies

Among the papers examined, a total of 476 model practices and case studies were identified globally (Fig. 2): North America (66.6%), Europe (14.5%), Asia (11.1%), Australia (3.6%), South America (2.7%), and Africa (1.5%). Another way to express the global distribution of case studies is to classify case studies by climatic zones: tropical (2.8%), dry (7.4%), subtropical (4.9%), temperate (44.9%), and continental (40.0%) (Fig. 3). The global distribution of case studies was uneven, with a majority of studies focused on urbanizing regions of temperate and continental climatic zones in the US, Europe and China; there were comparatively few studies of urban forest modeling in South America, Australia, and Africa.

With regards to scale, there were 8 papers conducted at a national level, 9 at a regional level, 61 at a city level, 8 at a watershed level, 49 at a local scale level, and 107 at a microscale level (Fig. 3). Both local and microscale levels are scales smaller than a city level. Local scale includes neighborhoods, communities, districts, planning zones, socioeconomic sub-regions, and other similar units, while microscale includes green roofs, buildings, parks, streets and other similar settings. Most of the studies were conducted at city, local and microscale levels, while some studies have been made at watershed, regional and national levels.

Inside the city, a variety of geographies have been employed in case studies, depending on the study purpose and discipline. Each discipline may identify a geographical unit or the most salient features associated with the unit differently (Grimm et al., 2000), such as a watershed (hydrology), land use or land cover types (geography), neighborhood or community (social science), and street canyon or building block (energy science). For the local scale, the most studied units were districts/communities with a total of 28 case studies; within the microscale, streets, parks, and green roofs received the most attention, with the numbers of case studies being 58, 22 and 25, respectively.

**Fig. 2.** Global distribution of urban forest case studies.

**Table 1**
Distribution of urban forest modeling papers among different fields.

| Fields | Journal Title | No. of Papers | Field Total |
|---|---|---|---|
| Environment | Environmental Pollution | 16 | 53 |
| | Atmospheric Environment | 12 | |
| | Journal of Environmental Management | 7 | |
| | Science of the Total Environment | 5 | |
| | Environmental Modelling & Software | 2 | |
| | Environmental Science & Technology | 1 | |
| | International Journal of Environment and Pollution | 1 | |
| | Environmental Management | 1 | |
| | Environmental Science and Pollution Research | 1 | |
| | Environment and Behavior | 1 | |
| | Journal of Environmental Planning and Management | 1 | |
| | International Journal of Environmental Science and Development | 1 | |
| | Atmospheric Pollution Research | 1 | |
| | Procedia Environmental Sciences | 1 | |
| | Ambio | 1 | |
| | AIMS Environmental Science | 1 | |
| Forestry and Arboriculture | Urban Forestry & Urban Greening | 34 | 48 |
| | Journal of Arboriculture | 5 | |
| | Arboriculture and Urban Forestry | 3 | |
| | Journal of Forestry | 2 | |
| | iForest-Biogeosciences and Forestry | 1 | |
| | Frontiers of Forestry in China | 1 | |
| | Journal of Sustainable Forestry | 1 | |
| | Forests | 1 | |
| Energy | Building and Environment | 16 | 37 |
| | Energy and Buildings | 15 | |
| | Solar Energy | 3 | |
| | Energy Procedia | 1 | |
| | Applied Energy | 1 | |
| | Building Simulation | 1 | |
| Landscape | Landscape and Urban Planning | 28 | 28 |
| Ecology | Urban Ecosystems | 7 | 14 |
| | Ecological Modelling | 2 | |
| | International Journal of Biodiversity Science, Ecosystem Services & Management | 2 | |
| | Ecological Applications | 1 | |
| | Ecosystem Services | 1 | |
| | Ecosystems | 1 | |
| Meteorology and Climatology | Theoretical and Applied Climatology | 4 | 12 |
| | Meteorologische Zeitschrift | 2 | |
| | Atmosphere | 2 | |
| | International journal of climatology | 1 | |
| | Boundary-layer meteorology | 1 | |
| | Advances in Meteorology | 1 | |
| | Journal of Applied Meteorology and Climatology | 1 | |
| Economics | Ecological Economics | 4 | 11 |
| | Journal of Forest Economics | 1 | |
| | Journal of Environmental Economics and Management | 1 | |
| | Land Economics | 1 | |
| | The Appraisal Journal | 1 | |
| | Australian Journal of Agricultural and Resource Economics | 1 | |
| | The Journal of Real Estate Finance and Economics | 1 | |
| | Forest Policy and Economics | 1 | |
| Geography | Urban Geography | 1 | 3 |
| | Moravian Geographical Reports | 1 | |
| | Chinese Geographical Science | 1 | |
| Other | Sustainable Cities and Society | 6 | 36 |
| | Sustainability | 5 | |
| | JAWRA Journal of the American Water Resources Association | 3 | |
| | Cities | 2 | |
| | Journal of Wind Engineering and Industrial Aerodynamics | 2 | |
| | Land Use Policy | 2 | |
| | Advances in Urban Rehabilitation and Sustainability | 1 | |
| | Journal of Sound and Vibration | 1 | |
| | Journal of Contemporary Water Research & Education | 1 | |
| | Agriculture and Agricultural Science Procedia | 1 | |
| | Remote Sensing of Environment | 1 | |
| | Spatial Demography | 1 | |
| | International Journal of Sustainable Development and Planning | 1 | |
| | Transportation Research Part D: Transport and Environment | 1 | |
| | Book Chapter | 4 | |
| | Official publication from USDA, National Recreation and Park Association and ENVI-met | 4 | |

### 4.2. Field-based analyses

Sixty-nine journals were identified over a wide range of fields (Table 1), revealing the transdisciplinary nature of this topic. Three fields interact closely and contribute the largest number of papers on this topic (in parenthesis are the number of papers and percentages, respectively): environment (53, 21.9%), forestry (48, 19.8%), and energy (37, 15.3%). The reason that the environmental field occupied the largest number of papers is due to the contribution from two journals: Environmental Pollution (16, 6.6%) and Atmospheric Environment (12, 5.0%). Thirty-four papers were published in Urban Forestry & Urban Greening, which makes forestry the next most common field. This field was followed by energy, with the largest contributions from Building and Environment (16, 6.6%) and Energy and Buildings (15, 6.2%). Other fields that also contribute to this topic were landscape (28, 11.6%), ecology (14, 5.8%), economics (11, 4.5%), climatology (12, 5.0%), and geography (3, 1.2%) (Table 1). This topic attracts attention from not only scientists, but also urban planners and policy makers, leading to papers in urban planning and management journals (e.g., Journal of Environmental Management, Environmental Management).

### 4.3. Urban forest models

Urban forest case studies have been analyzed and simulated using a wide range of models (Table 2). In terms of numerical models, they can be roughly divided into two categories: general-purpose models (ENVI-met, computational fluid dynamics (CFD), Green Cluster Thermal Time Constant (Green CTTC), DOE-2 building-energy simulation program (DOE-2), and Solar and Longwave Environmental Irradiance Geometry (SOLWEIG)), and urban forest-specific models (i-Tree, CITYgreen). The detailed description of these models can be found in the Supplementary Material to this paper.

i-Tree is the most dominant model used in urban forest modeling (Table 2). i-Tree and ENVI-met are toolsets, including various sub-tools or modules (Table 3). Of the various i-Tree toolsets, Eco (formerly UFORE) was implemented most frequently, although case studies can also be found using Streets (formerly STRATUM), Hydro, Canopy, and Species. The next widely used models are ENVI-met and CFDs. For ENVI-met application, the typical approach is based on a scenario comparison of designed or real landscapes (e.g., with/without trees, tree configuration, tree-building spatial layouts) (e.g., Skelhorn et al., 2014; Salata et al., 2015; Morakinyo and Lam, 2016). CFD is a collection of models that are based on the fundamental laws of fluid mechanics and thermodynamics. Typical applications of CFD include the thermal effects of trees on surrounding buildings and pedestrian environments (e.g., Dimoudi and Nikolopoulou, 2003), and removal and trapping of air pollutants from road traffic due to trees' deposition effects, filtering capacity, and aerodynamic effects (e.g., barrier, ventilation performance) (e.g., Jeanjean et al., 2015; Amorim et al., 2013). Detailed principles, processes and parameterizations of CFDs can be found in Buccolieri et al.'s (2018) review of urban tree CFD modeling. Unlike i-Tree, which emphasizes the impact of different tree aspects,

**Table 2**
Summary statistics of urban forest models.

| | Citations | Country | Case studies | Publications |
|---|---|---|---|---|
| i-Tree | 8461 | 21 | 264 | 76 |
| ENVI-met | 2614 | 18 | 50 | 43 |
| CFD | 2206 | 8 | 35 | 35 |
| CITYgreen | 305 | 2 | 8 | 6 |
| Green CTTC | 881 | 3 | 7 | 7 |
| DOE-2 | 1658 | 2 | 24 | 5 |
| SOLWEIG | 222 | 3 | 4 | 4 |
| Hedonic price model | 2996 | 10 | 40 | 32 |
| Others | 2710 | 10 | 44 | 34 |

**Table 3**
Characteristics of the main numerical urban forest models.

| Models | Initial release & current version | Sub-modules & web references | Free & open source or not | User programming knowledge required (low, medium, high) | Uncertainty assessments (No, limited, developed) | Spatially explicit or not |
|---|---|---|---|---|---|---|
| i-Tree | 1996; Version 6 | Eco, Hydro, Streets, Vue, Species, Canopy, Design, & Landscape: https://www.itreetools.org/[a] | Yes / No | Low | Limited | Yes for specific modules |
| ENVI-met | 1994; Version 4.3 (As of Nov 2017) | Atmospheric, Vegetation, Soil, and Built environment & Building system: http://www.envi-met.com/ | Yes / No | Low | Limited | Yes |
| CFD | 2004; Version 1712 (As of Dec 2017) | Open Field Operation and Manipulation (OpenFOAM) http://www.openfoam.com | Yes / Yes | High | Limited | Yes |
| | 1996; Version 19.1 (As of May 2018) | ANSYS' Fluent https://www.ansys.com/products/fluids/ansys-fluent | No / No | Medium | Limited | Yes |
| | 1981; Version 2018 | CHAM's PHOENICS http://www.cham.co.uk/ | No / No | Medium | Limited | Yes |
| | 1989; Version 6.3 (As of July 2014) | Lohmeyer's Microscale Flow and Dispersion Model (MISKAM): http://www.lohmeyer.de/en | No / No | Medium | Limited | Yes |
| CITY-green | 1996; Version 5 (As of March 2004) | None | Yes /No | Low | No | No |
| Green CTTC | 2002; None | None | None | None | Limited | No |
| DOE-2 | 1978; Version 2.3 (As of July 2017) | http://doe2.com/ | Yes / No | Medium | Limited | No |
| SOLWEIG | 2008; Version 2016a (as of Sept 2016) | http://www.urban-climate.net/content/ | Yes / Yes | Medium | Limited | Yes |

[a] The last access of weblink is July 2018.

**Table 4**
Number of case studies assessing urban forest ES.

| Ecosystem services | 1996-2010 (#/year) | 2011-2017 (#/year) | 1996-2017 Total # |
|---|---|---|---|
| **Physical/Biological Benefits** | | | |
| **Removal of Air Pollutants** | | | |
| Remove course particulate matter (PM10) | 1.2 | 5.1 | 54 |
| Remove ozone ($O_3$) | 1.2 | 4.8 | 52 |
| Remove nitrogen dioxide ($NO_2$) | 0.9 | 4.8 | 47 |
| Remove carbon monoxide (CO) | 0.9 | 3.7 | 40 |
| Remove sulfur dioxide ($SO_2$) | 0.7 | 3.6 | 36 |
| Remove fine particulate matter (PM2.5) | 0.0 | 2.4 | 17 |
| Remove volatile organic compounds (VOCs) | 0.5 | 1.0 | 15 |
| Remove elemental carbon (EC) | 0.0 | 0.3 | 2 |
| Remove nitrogen monoxide (NO) | 0.0 | 0.2 | 1 |
| Remove ultraviolet (UV) radiation | 0.0 | 0.2 | 1 |
| **Temperature and Microclimatic Modifications** | | | |
| Lower air temperature | 1.4 | 3.0 | 42 |
| Provide tree shade | 1.0 | 0.7 | 20 |
| Reduce urban heat island (UHI) | 0.1 | 1.4 | 12 |
| Provide evaporative and transpiration cooling | 0.3 | 0.4 | 8 |
| Provide park cool effect | 0.1 | 0.9 | 8 |
| Regulate wind | 0.1 | 0.9 | 8 |
| Reduce incoming solar radiation | 0.0 | 0.3 | 2 |
| **Carbon storage and sequestration** | | | |
| Carbon storage and sequestration | 0.9 | 3.5 | 39 |
| **Storm water regulation** | | | |
| Reduce runoff | 0.9 | 1.9 | 26 |
| Improve water quality | 0.0 | 0.3 | 2 |
| **Other** | | | |
| Wildlife and biodiversity | 0.1 | 0.2 | 3 |
| Noise effect | 0.0 | 0.2 | 1 |
| **Economic Benefits** | | | |
| Reduce building energy use (e.g., heating, and cooling) | 1.5 | 2.3 | 39 |
| Increasing property value or rent price | 1.3 | 2.3 | 36 |
| Aesthetic quality | 0.1 | 0.4 | 5 |
| **Social Benefits** | | | |
| Thermal comfort/heat stress | 0.1 | 2.0 | 15 |
| Crime rate | 0.1 | 0.6 | 5 |
| Human health and disease | 0.1 | 0.3 | 3 |
| Environmental inequality | 0.0 | 0.3 | 2 |

ENVI-met and CFDs also simulate the impacts of street and building characteristics (e.g., sky view factor, road traffic volume, canyon geometry, and ground and building materials) (e.g., Wania et al., 2012; Tan et al., 2016; Salata et al., 2015; Shahidan et al., 2012). As such, ENVI-met and CFDs are also employed in the areas of landscape architecture, building design, and energy and environmental planning (Ambrosini et al., 2014).

Although not as widely used as the above-mentioned models, CITYgreen, Green CTTC, DOE-2, and SOLWEIG are also frequently employed (Table 2). CITYgreen had many applications from 1996 to 2006, but became less used afterwards due to model limitations (Longcore et al., 2004) and probably the increased use of i-Tree tools. Both DOE-2 and SOLWEIG also have applications in building energy analysis, emphasizing the impacts of building characteristics (e.g., building layouts, constructions, conditioning systems, and shade patterns of walls) on energy usage (Akbari et al., 2001; Lindberg and Grimmond, 2011). While other models were also represented, their contributions were minimal. For example, Shadow Pattern Simulator is found in three case studies examining tree's effect on residential energy use and indirectly carbon reduction (e.g., Simpson and McPherson, 1998; Jo and McPherson, 2001). Only two case studies use the fine resolution atmospheric multi-pollutant exchange atmospheric transport model (e.g., McDonald et al., 2007) and the coupled weather research and forecasting and urban canopy model (Loughner et al., 2012). One case study was found utilizing the vegetated urban canopy model (Lee, 2011), and the CHIMERE air quality model (Alonso et al., 2011).

Regarding statistical models, 45 papers and 60 case studies were identified over the study period. Three characteristics can be summarized. First, statistical models often have a strong economic focus, and consider issues such as an urban forest's impact on property values (Donovan and Butry, 2010), rental rates (Laverne and Winson-Geideman, 2003), and energy savings (Pandit and Laband, 2010). Second, 18 out of 45 papers adopted a spatially explicit approach. Even for some models adopting a non-spatial approach, they considered spatial effects indirectly by employing location or distance factors as predictor variables (Tyrväinen, 1997; Laverne and Winson-Geideman, 2003; Morancho, 2003). Finally, among the 45 papers focusing on statistical models of urban forests, 32 papers used Hedonic price modeling, a method to estimate the contribution of ecosystem or environmental services to the value of a property (Sander et al., 2010) (Table 2).

Two characteristics of models are also investigated: spatial explicitness and uncertainty. A model is spatially explicit when the inputs, outputs or processes vary spatially (Turner and Gardner, 2015). ENVI-met, CFD, SOLWEIG, i-Tree Design and i-Tree Landscape are spatially explicit models, while other models investigated are generally not spatially explicit (Table 3). Uncertainty, due to incomplete information or the lack of knowledge of underlying processes, is a fundamental characteristic of any model (Wu et al., 2006). Uncertainty is generally insufficiently evaluated or overlooked in current urban forest models (Table 3). Uncertainty assessments are usually something added after the model has already been developed. For example, in models such as ENVI-met, Green CTTC, and SOLWEIG, only model output uncertainty (or prediction error) is assessed and expressed as the discrepancy between the model predictions and observations (e.g., Wu and Chen, 2017; Shashua-Bar and Hoffman, 2002; Lindberg and Grimmond, 2011). In addition, only specific kinds of uncertainty are typically assessed. For example, in i-Tree, only sampling error of field plot data is evaluated while other kinds of uncertainties (e.g., model structure and parameter uncertainty) are ignored, resulting in the underestimation of the overall uncertainty (Nowak et al., 2013). None of the papers address uncertainty in communication of model output to the public and decision-makers.

In terms of acquiring input datasets, 164 papers employed only bottom-up approaches, while 78 papers used the top-down approaches relying on remotely sensed imagery (Fig. 3), including aerial photographs, AVHRR, Landsat, MODIS, LiDAR, NLCD, TRMM, IKONOS, and QuickBird imagery. Fifty-four of the 78 papers were published after year 2011, indicating the increasing utilization of remotely sensed imagery. A wide range of top-down approaches were employed to derive different model inputs. For example, MODIS has been used to estimate leaf area index (e.g., Nowak et al., 2014), and high resolution digital imagery and Landsat data have been employed to estimate tree canopy and land cover types (e.g., Morani et al., 2011; Yang et al., 2005).

### *4.4. Ecosystem services estimated with urban forest models*

ES found in the papers examined were classified into three categories: biophysical, social and economic (Table 4). Biophysical benefits had 432 case studies, which was much higher than economic benefits (80) and social benefits (25), indicating an uneven distribution of case studies. Of the 432 case studies examining biophysical benefits, air pollutant removal was ranked highest with 264 case studies, followed by temperature and microclimatic modifications (98), carbon storage and sequestration (39), and water regulation (28). There were also three case studies analyzing wildlife and biodiversity, and one case study focused on noise effects. Regarding economic benefits, the most dominant topics were building energy cost reduction (e.g., cooling effects, heating effects) (39) and increased property values (36), followed by aesthetic quality (5). Among social benefits, thermal comfort received the most attention with 15 case studies, followed by reduced crime rate (5) and human health and disease (3).

In terms of new emerging topics, there appears to be an evolution in urban forest modeling. While studies of biophysical benefits continue to be most common, studies of fine particulate matter ($PM_{2.5}$), ultraviolet light, elemental carbon, and water quality appeared only after 2011. Assessing the impacts of urban forests on these issues increases the diversity of urban forest ES and presents new challenges and opportunities in urban forest modeling. Some topics (e.g., urban heat island, park cool effect, thermal comfort, human health and disease) show an increasing rate of study after year 2011, indicating a potential increasing trend in the future.

## 5. Discussion

### 5.1. Place-based, comparative studies

#### 5.1.1. Distribution of case studies

The systematic review presented here assesses and compares urban forest modeling practices among places and across scales. We identified that: (1) the spatial distribution of case studies is clustered around certain locations (e.g., US, Europe and China and mostly in temperate and continental climatic zones); (2) most of the studies were conducted at and below city scales, and only a few studies were made at regional or national scales; and (3) within cities, the most popular units were parks and individual streets. The popularity of specific locations, cities and units could be attributed to several factors. The US and Europe are highly developed areas while China is one of the most rapidly developing countries; all have a large number of cities and associated various kinds of urban environmental issues. As such, cities in those areas provide ideal natural laboratories for urban forests studies. In addition, some models (e.g., ENVI-met, CFD) are designed for microscale simulations, and thus favor units like parks and street canyons. Urban forest studies in these areas are generally more comprehensive, and these studies have the potential to provide information to support future urban forest studies in less-studied regions.

These analyses contribute to our understanding of the structure, function, and benefit of urban forests, and the interactions between social and natural systems. Unfortunately, the uneven and fragmented distribution of case studies may bias our knowledge and understanding of urban forestry. Each place is unique in its own way and findings for one city can be quite different than for another city. For example, Nowak et al. (2004) performed computer modeling of air pollution removal by trees in 55 US cities and their results showed that pollution removal per unit canopy cover varied significantly from place to place, depending on pollution concentrations, length of in-leaf season, amount of precipitation, and other meteorological variables. Overall, management of urban tree canopy cover could be a viable strategy to improve air quality. However, Setälä et al. (2013) studied two Finnish cities and concluded that the ability of urban vegetation to remove air pollutants is minor in northern climates considering the short growing season. Vos et al. (2013) conducted a computer simulation and reached the conclusion that trees can deteriorate air quality at least locally at roadside locations based on summary of 17 scenario simulations of various vegetation settings. Conclusions about air pollution removal effects are clearly location- and scale-specific, and caution is needed when generalizing results. Regarding carbon storage, based on the studies of 28 cities and 6 states in the US, carbon density per unit of tree cover varied among cities based on tree density, tree size distributions, and species composition, with the general pattern of forested regions having greater carbon densities than grassland or desert regions (Nowak et al., 2013a). In terms of carbon sequestration, depending on which models you employ (e.g., i-Tree Streets, allometric equations from Urban Tree Database, or other empirical equations), the differences among the magnitudes of carbon sequestration estimates can be up to a factor of 2 (Boukili et al., 2017). Apart from the magnitude, the direction (e.g., from source to sink) can also vary. Based on two studies in Singapore and Mexico City, Velasco et al. (2016) concluded that carbon sequestration by urban trees are both positive, but when including soil respiration effects, overall carbon sequestration is negative, i.e. the trees and soil in Singapore act as a carbon source and not a sink. Soil respiration is typically ignored due to large areas of impervious surfaces in cities. Even within one city, the impact of location cannot be neglected. For example, in terms of cooling effects and human thermal comfort, avenue-trees often have the strongest impact, façade greening has some noticeable effect, and roof greening is mostly ineffective (Ng et al., 2012; Gromke et al., 2015). Trees also appear to perform differently depending on their placement within a unit (such as the leeward, windward, central, and end parts of street canyons) (Moonen et al., 2013). The compilation of numerous case studies, while uneven, can give indications of commonalities and ranges of urban forest effects in different cities.

#### 5.1.2. Scale and study unit

Apart from the uneven spatial distribution of case studies, there is also a gap between local research and global generalizations. Local scale research is important and the existing literature illustrates and discusses the need of local forest structure (Escobedo & Nowak, 2009; Nowak et al., 2013a) and local scale tree design (Nowak et al., 2013b). However, due to spatial heterogeneity (Escobedo & Nowak, 2009), urban trees may have opposing effects at different scales (Vos et al., 2013), and there is the need for multi-scale approaches (Jeanjean et al., 2015). Caution is needed to generalize findings among different places and scales, but by understanding the physics, chemistry, biology and social structure of urban forests, generalized principles can be developed to guide urban foresters in designing forest structure to optimize ES.

Another concept that is related to scale is the study unit. Different units provide different perspectives, and only through integration of a variety of units can a comprehensive view of urban forestry be achieved. For example, focusing on street canyons, the conclusion that roadside trees negatively affect the local air quality may be obtained under certain conditions (Ries and Eichhorn, 2001; Wania et al., 2012). However, this does not indicate that trees in urban backyards and parks have a similar effect (Vos et al., 2013). More studies are needed to integrate different units and scales. Two challenges exist when considering different study units. First, the increased focus on ecological units and integration of ecological and political units should be pursued in the future. Existing studies focus mostly on political units (e.g., census block groups), while ignoring ecological units such as patches, habitats and ecoregions. Units important to humans are not necessarily relevant for tree species or ecological processes, but help convey information in units important to managers, planners and politicians. The boundaries of different units, such as watersheds and administrative districts, may not coincide. In addition, mismatch between units or scales of ecological processes and the institutions that are responsible for managing them can contribute to decision failures (Cumming et al., 2006). Second, spatially heterogeneous representation of landscapes can be classified as a mosaic, which include patches and corridors with abrupt discontinuities or boundaries, and gradients with gradual differences in concentrations (Forman, 1995). Most studies reviewed in this paper focus on urban mosaics and ignore gradient approaches. This is mainly because the boundaries must be explicitly defined under most modeling frameworks. Due to practical need, boundaries are usually defined where several discontinuities coincide (MEA, 2005). Although gradient areas (e.g., urban-periurban-rural, wildland-urban interface) have been intensively studied in ecology (Openshaw, 1984), geography (Kwan, 2012), and even urban forestry (Zipperer et al., 1997) using approaches such as landscape metrics, spatial statistics, and transect analyses (Luck and Wu, 2002; Kong and Nakagoshi, 2006), few studies incorporate these ideas or principles in urban forest modeling.

## 5.2. Field-based analyses

Urban forestry has developed rapidly (Fig. 1) due to contributions from many fields (Table 1). For example, the concept of sustainable urban forestry is largely based on sustainability concepts from the ecology field (Fazio, 2003); the theories about scale and spatial heterogeneity from geography contribute greatly to spatially explicit research of urban forests (Escobedo & Nowak, 2009); the laws of fluid dynamics and thermodynamics from energy science improve our understanding of interactions between surface, vegetation and the atmosphere (Bruse & Fleer, 1998); and landscape ecology principles are used in the design and planning of urban green spaces (Zhou et al., 2011). Urban forestry is interdisciplinary by fusing knowledge from several fields, and transdisciplinary by applying scientific knowledge in policy-relevant ways. Transitioning more urban forestry initiatives and studies from interdisciplinary to transdisciplinary could be of great benefit. For example, with volunteer public participation, the MillionTrees program and 10-year cycle street tree census (2015–2016) in New York City have been implemented more efficiently (NYC Parks, 2018). Discipline-bound approaches conflict with the nature of urban forestry because by definition urban systems are social-ecological, and urban forests provide a wide range of ES which are of common interest to multiple disciplines. Urban forestry not only concerns itself with scientific research, but also involves in management, planning, education and outreach (Moskell et al., 2010; Rae et al., 2010).

## 5.3. Urban forest models

### 5.3.1. Numerical models

A wide range of urban forest models exist, each suitable for specific applications. i-Tree and ENVI-met are two of the most widely used models (Table 2), most likely because they are freely available, do not require user programming experience, and contain various modules for different applications (Table 3). One additional reason that i-Tree is the most widely used is that it can be used at new locations or conditions without the re-calibration of model parameters. This is different from approaches adopted by other models (e.g., ENVI-met, CFD); when applying models outside their original modeling domains, new site-specific parameter values must be obtained from measured data. i-Tree eliminates the need of parameter calibration by developing i-Tree databases, that contain tree species and location information for many countries to support modeling at new locations (see Supplementary Material). When site-specific parameters are insufficiently calibrated or unavailable, model outputs tend to contain large uncertainties (Walker et al., 2003). CFD models also have many applications for tree temperature effects (e.g., interaction with buildings characteristics), and air pollution removal effects (e.g., interaction with street characteristics and road traffic volume). One limitation of CFDs is that they usually require medium to high user programming experience (Table 3). When quantifying trees' thermal and building energy effects is a focus, Green CTTC, SOLWEIG, and DOE-2 are also potential choices.

### 5.3.2. Statistical models

Statistical models tend to be empirical and subjective due to the selection of predictor variables and functional forms. It is often the case that in one paper, several functional forms are developed, the structures and forms of statistical models often are identified based on the empirical fitting to observational datasets, and comparisons of different fittings are conducted using statistical measurements (e.g., the goodness-of-fit test) and information criteria (e.g., Akaike Information Criterion) (Conway et al., 2010; Sander et al., 2010; Pandit et al., 2013). The resultant best selected model can provide a useful description of the system even without physiological or mechanical knowledge (Jones, 2013). The problems of this approach are that (1) across papers, model forms and explanatory variables can vary widely which makes comparative studies challenging; and (2) the model may only be valid where it is developed and calibrated; caution is needed when generalizing the model to other locations, or when model-based inferences are performed. Future applications of statistical models in urban forestry should emphasize the use of theoretical guidance towards the selection of appropriate model structure and predictor variables.

### 5.3.3. Spatially explicit modeling

Although spatially explicit modeling can increase model complexity and data burden (Turner and Gardner, 2015), the spatial distribution of trees and their associated ES is essential for designing effective and equitable policy interventions (TEEB Foundations, 2010). The production, flow and use of ES varies spatially, as do the spatial patterns of beneficiaries and policy interventions. In addition, apart from the number of trees, the spatial composition and configuration of trees can also affect the ES they provide (e.g., Li et al., 2012; Zhou et al., 2017). ENVI-met, CFD and SOLWEIG are designed to be spatially explicit; the i-Tree tool suite is also transforming from lumped to spatially explicit modeling, with two new modules, i-Tree Design and Landscape, that can provide location information at local and landscape scales, respectively. Spatially explicit approaches are also often adopted by statistical models directly by using spatial regression or indirectly by employing location or distance factors as predictor variables. Providing equivalent tree cover per capita (or per land area) and accessibility to green space, especially for underrepresented or disadvantaged groups, could be a top priority for future urban forest management programs. Better quantifying the composition and configuration of trees and its influences on ES will also benefit forest management.

### 5.3.4. Model uncertainties

Although the importance of uncertainty in modeling is well recognized (Walker et al., 2003), few studies of urban forest modeling provide critical information about model uncertainties. For those models that do provide uncertainty information, only specific kinds of uncertainties (e.g., sampling error, prediction error) are typically considered. This may be due to two reasons. First, for existing models that describe complex ecosystem interactions (e.g., i-Tree, ENVI-met), a full and thorough uncertainty assessment (especially quantification and reduction) usually involves significant changes to model architecture (e.g., model assumptions, simplifications, formulations, and parameterizations). The lack of time and funding given other competing priorities of model developments limits current uncertainty assessments. Second, although uncertainty assessment methods are well-developed (Refsgaard et al., 2007), no method is universally applicable and effective for all models. Guidance to select appropriate methods for specific model types and applications is lacking, plus each method has a learning curve (Pappenberger and Beven, 2006), which further limits uncertainty assessment. Given the importance of uncertainty analyses, especially for those models focused on policy- or decision-making, future modeling exercises could focus on improving the assessment and communication of uncertainty. Incorporating uncertainty assessment at the beginning of problem framing and model framework design, and tracking and documenting uncertainty throughout model development could significantly reduce overall efforts to incorporate uncertainty analyses in urban forest models.

### 5.3.5. Model comparisons

The comparison and integration of numerical models is rare, with only a few studies on model integration (e.g., Tiwary et al., 2009; McPherson & Kotow, 2013; Morakinyo and Lam, 2016) and model comparison (e.g., Russo et al., 2014; Guidolotti et al., 2016). General comparisons of models and model outputs may not be useful, and sometimes can even be misleading. Different models can estimate similar ES based on different input variables, model assumptions and formulations. For example, when estimating trees' temperature effects, a CFD model is based on the fundamental laws of fluid mechanics and thermodynamics to simulate the effects of vegetation on transpirational cooling and mean air flow and turbulence (e.g., Gromke et al., 2015). Contrary to this, Green CTTC employs an energy balance approach which quantifies anthropogenic heat-release, reduction of the solar gain due to tree canopy, energy consumption for evapotranspiration, and the change in the heat stored based on leaf surface temperature (Shashua-Bar & Hoffman, 2004). In this case, the differences in a tree's temperature effects could be due to different modeling approaches rather than a tree's structure and function. However, this does not mean that model comparisons should be avoided. Modeling experiences from other fields (e.g., public health, agriculture crop yield) have shown that the combined information of several models is superior to that of a single model (Thomson et al., 2006; Cantelaube and Terres, 2005). The way models are compared and integrated is important. Model comparisons and integration can be conducted at the decision-making level; if different models, with dissimilar theoretical foundations, reach similar conclusions about the effects of urban forests, it will increase the confidence of urban forests management decisions based on such similar conclusions, especially when uncertainty analyses are lacking.

### 5.3.6. Input datasets

Remotely sensed images play an important role in urban forest modeling. This is mainly due to increased availability of free remotely sensed imagery (Patino and Duque, 2013), and many ready-to-use image derived products (e.g., vegetation index, leaf area index, tree canopy cover) (O'Neil-Dunne et al., 2014; Morani et al., 2011; Yang et al., 2005). Although there is a trend of increasing utilization of remotely sensed imagery, this information mainly serves as input variables for urban forest models. A closer connection between remote sensing and urban forest modeling is needed, which will open up additional possibilities for future research and innovation. Two-dimensional images may greatly improve our ability to perform spatially explicit modeling, and long-term archives of time-series images present an opportunity to improve our understanding of the dynamics of urban forests and the impacts of these changes. In addition, remote sensing can sometimes aid in validating models (e.g., biomass, LAI) (Lu et al., 2016; Alonzo et al., 2016), which reduces model uncertainties and increases the credibility of a model and its outputs.

## 5.4. Ecosystem services estimated with urban forest models

### 5.4.1. Biophysical, economic and social benefits

Most case studies focus on biophysical benefits while only a few estimate economic and social benefits. This disparity may be due to significant advances we have achieved in linking forest structure to function. For instance, we have a good understanding of how a tree's characteristics (e.g., albedo, surface roughness) and biophysiological processes (e.g., evapotranspiration, storing carbon) affect temperature (Bonan, 2008), and how trees uptake and remove air pollution by dry deposition processes (Hirabayashi et al., 2011). We are able to parameterize these attributes and formulate these processes explicitly in models. However, we have limited capability to simulate economic and social benefits due to a lack of theory and large subjectivity and uncertainty in expressing and quantifying human cultures, values, attitudes and behaviors in models. For example, trees can provide amenity services to increase property values (e.g., Payton et al., 2008; Sander et al., 2010). However, amenity services (e.g., aesthetic enjoyment, recreation, intellectual development, and spiritual fulfillment) are influenced and shaped by human cultures, knowledge systems, religions, and social interactions (MEA, 2005). As such, quantifying those benefits suffers from large uncertainties and biases. In terms of social benefits, for instance, trees can affect human health by reducing air pollutant concentrations, but valuing the effects suffers from subjectivity due to the cost of illness, willingness to pay to avoid illness, and productivity losses associated with health events (Nowak et al., 2014). Different individuals have different 'behavioral patterns, dietary patterns and physiological characteristics (e.g., breathing rates)' (WHO, 2008), which adds additional complexity to model the effects of air pollutant exposure. Although challenging, human behaviors and values are well modeled in other fields (e.g., economic, political ecology) (Anderies, 2000; Peterson, 2000); those advanced experiences should benefit future urban forest modeling. The linkages between forest structure and biophysical benefits is well understood and modeled, and ES delivery in biophysical terms also provides solid ecological underpinnings to economic and social metrics (TEEB Foundations, 2010). Expanding the links to incorporate trees' social-psychological and health effects, as well as quantifying and valuing those effects, is a priority area where additional work is needed.

### 5.4.2. Health-related ES

Studies regarding the health-related ES of trees increased after 2011, compared to the period 1996-2010. These include 'thermal comfort/heat stress' and 'human health and disease' from social benefits, as well as various kinds of air pollutant removals (e.g., particulate matter, ozone), which have important health implications (Kinney, 2008). Many ES are public goods, and people usually lack direct incentives to protect and maintain them (TEEB Foundations, 2010). One of the key challenges facing urban forest campaigns is to get the attention and involvement of different stakeholders (Zhang et al., 2007), and human health is one of the few ES that is relevant to almost everyone. Emphasizing the health effects of trees is an effective strategy to convey the importance of urban forests and gain support from stakeholders.

### 5.4.3. Ecosystem disservices

Another aspect that is less studied is ecosystem disservices (EDS) of urban forests. Common examples of EDS found in the literature include biogenic volatile organic compound emissions (Calfapietra et al., 2013), increases in potential energy use (Nowak et al., 2017), allergenic effects (Dobbs et al., 2014), air pollution trapping at road sites (Vos et al., 2013), and gentrification (Wolch et al., 2014). Although the adverse effects of urban forests have been mentioned and discussed in several papers (e.g., McDonald et al., 2007; Buccolieri et al., 2009; Morani et al., 2011), there are few studies to simulate and quantify EDS (Vos et al., 2013; Nowak et al., 2013b), let alone integrate EDS in decision-making. Since EDS are often ignored, the overall net benefits of urban forests may be less than initially estimated. The combined effects of ES and disservices and their influence on urban forest management and decision making are rarely investigated.

### 5.4.4. ES interactions

Regarding individual ES, the majority of papers explore specific types of ES while ignoring the interaction among different ES. These interactions can happen at different levels. For instance, for air pollutant removal, most studies estimate the removal of $PM_{10}$, $O_3$, CO, $NO_2$, and $SO_2$ in parallel. This makes sense for primary gases (e.g., $NO_2$, $SO_2$), but not for secondary gases (e.g., ozone), which can be created through complex chemical reactions and interactions (Pickett et al., 2011; Morani et al., 2011). Ignoring these interactions will lead to inaccurate estimation of net ozone effects (Cabaraban et al., 2013). At a higher level, the change of one ES could also affect other kinds of ES. For example, temperature reductions have implications for energy use, air quality, and human health (Nowak et al., 2014); energy savings can result in reduced emissions of $CO_2$ and air pollutants (McPherson et al., 2017; Nowak et al., 2017). Those interactions, either positive synergies (multiple services are enhanced simultaneously) (Bennett et al., 2009) or negative tradeoffs (the provision of one service is reduced as a consequence of the increased use of another) (Turner and Gardner, 2015), are commonplace in ecosystems (MEA, 2005). In contrast to the above common definition of tradeoffs, Mouchet et al. (2014) also refers to tradeoffs as various types of compromises, such as management compromises between ES. For instance, are tree species and locations being chosen to maximum or prioritize air pollution removal benefits or energy conservation benefits? Urban forest management decisions should consider these interactions and compromises to better avoid tradeoffs and enhance synergies.

## 6. Future directions and conclusions

Future directions in urban forest modeling can be organized around three key themes: urban systems, model development, and ES. An urban system is a complex and adaptive socio-ecological system which is characterized by spatial dependence and heterogeneity. However, urban ecosystems are often modeled non-spatially, which can ignore some local or microscale effects and interactions due to spatial arrangements. Future studies of urban forestry could focus on: (1) summarizing and generalizing experiences from well-studied regions (e.g., US, Europe, China) to support urban forest studies in less-studied regions; (2) multi-scale approaches to capture interactions among spatial heterogeneity at the local scale, and interaction among cities, suburbs, and their regional background environments at the regional scale; (3) improving linkages between ecological processes and social organization scales to improve urban forest modeling, planning, management and stewardship. With regards to model development, future research could focus on (1) improving uncertainty analyses, (2) employing spatially explicit expressions of location information, including issues related to environmental justice, (3) comparing and integrating models at a policy-making level, (4) increasing utilization of remote sensing, (5) increasing model capability to incorporate the effects of human cultures, values, attitudes and behaviors, and (6) increasing mechanistic understanding and its integration into statistical models. In addition, more effort could be devoted to model training to engage broader audiences and better utilize existing software, and to better communicate model outputs to stakeholders and decision-makers. In terms of ES, emphasis could be put on: (1) expanding linkages between forest structure and function to incorporate trees' social-psychological and health effects, (2) quantifying and valuing EDS, and (3) investigating ecosystem service synergies and tradeoffs.

With well-developed scientific rationales, models serve as a basis for collaboration and knowledge exchange between academic researchers and non-academic participants, and provide a scientific means to achieve sustainable urban forestry. Urban forest modeling is becoming increasing complex, global, and transdisciplinary, and this trend is likely to continue. As such, there is an urgent need for comparative studies and studies across a wide range of geographic settings. By synthesizing case studies from the perspectives of places, units, scales, disciplines, tools, and topics, this review provides insights and suggestions for future urban forest modeling research. Such knowledge can improve urban forest planning, design and management, and better support critical policy- and decision-making processes.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2019.126366.

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