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Review

A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones

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ABSTRACT

Urban trees can potentially mitigate environmental degradation accompanying rapid urbanisation via a range of tree benefits and services. But uncertainty exists about the extent of tree benefits and services because urban trees also impose costs (e.g. asthma) and may create hazards (e.g. windthrow). Few researchers have systematically assessed how urban tree benefits and costs vary across different cities, geographic scales and climates. This paper provides a quantitative review of 115 original urban tree studies, examining: (i) research locations, (ii) research methods, and (iii) assessment techniques for tree services and disservices. Researchers published findings in 33 journals from diverse disciplines including: forestry, land use planning, ecology, and economics. Research has been geographically concentrated (64% of studies were conducted in North America). Nearly all studies (91.3%) used quantitative research, and most studies (60%) employed natural science methods. Demonstrated tree benefits include: economic, social, health, visual and aesthetic benefits; identified ecosystem services include: carbon sequestration, air quality improvement, storm water attenuation, and energy conservation. Disservices include: maintenance costs, light attenuation, infrastructure damage and health problems, among others. Additional research is required to better inform public policy, including comparative assessment of tree services and disservices, and assessment of urban residents and land managers' understanding of tree benefits and costs.

Introduction

Rapid urbanisation is destroying natural ecosystems and degrading the environmental quality of towns and cities (Folke et al., 1997; Gregg et al., 2003; Alberti and Marzluff, 2004). In recent decades, rates of urbanisation have intensified globally; over half of the world's population now inhabits cities, and 10% lives in megacities of 10 million or more (United Nations, 2010). By 2050, this will be closer to 75% (Roberts, 2011). Many cities have been experiencing unprecedented growth, accompanied by severe environmental degradation (e.g. noise, carbon pollution, soil erosion, habitat loss, and species extirpation) (Zipperer et al., 1997; Vesely, 2007; Young, 2010). Scholars and policy-makers have begun to direct their attention to evaluating the potential of urban trees to ameliorate some of this harm (Girardet, 1996; Hough, 2004; Register, 2006; Newman and Jennings, 2008).

Urban tree research has examined various aspects of trees (including ecosystem services and disservices), but a comprehensive assessment of this research is lacking. What is needed is a systematic assessment of: methods that have been used, where has research occurred, what studies have found, and where the most important gaps in the literature occur. This paper systematically analyses the literature on urban tree benefits and disbenefits (including ecosystem services and disservices) and assessment methods. The paper seeks to answer four research questions: (1) how have different studies assessed urban tree costs and benefits (e.g. field methods vs. remote sensing)?; (2) how do the results of different cost–benefit studies on urban trees compare?; (3) is there a common measure showing the same benefit or cost for the same trees in different cities in different climate zones?; and (4) are there similar benefits and costs of urban trees in different parts of the world, and if so, what are they, and what factors are driving these similarities?

The paper begins by concisely defining the key terminology ('urban tree', 'urban forest', 'green-space', 'benefits', 'costs', 'ecosystem services' and 'ecosystem disservices') and then discusses the

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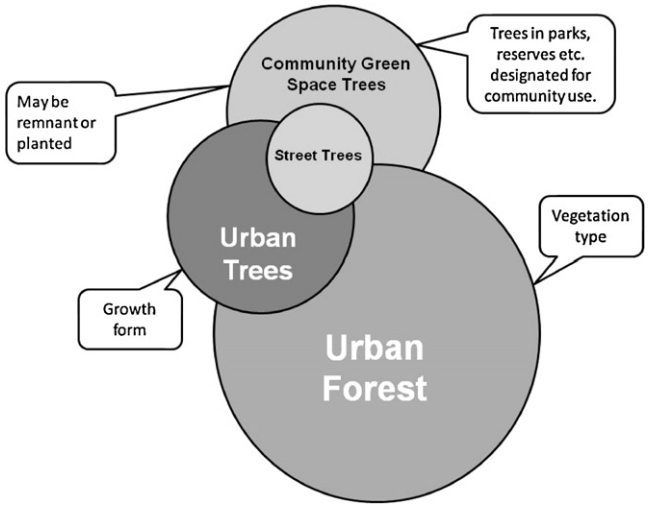

Fig. 1. Conceptual framework explaining the domain of urban trees.

methods used in this study. Results of the systematic exploratory review of urban tree literature are then reported and discussed. Some suggestions are then made for future research and the paper concludes by identifying implications for urban policy. It should be noted from the outset that this paper is not about ecosystem services and disservices per se; rather it considers the benefits and costs of urban trees, some of which include ecosystem (dis)services. For this reason, the paper addresses issues beyond the purview of the ecosystem services literature.

Seeing the trees from the forest – definition of key terms

Few studies of urban trees have actually defined what is meant by the term 'urban tree' and 'green-space' (Vesely, 2007 is a notable exception). Indeed Randrup et al. (2005) have observed that questions about: "which types of green-space and which areas ... to include [in research] have not been answered unambiguously". For the purpose of this paper, an urban tree is a woody perennial plant growing in towns and cities, typically having a single stem or trunk – and usually a distinct crown – growing to a considerable height, and bearing lateral branches at some height from the ground. Urban trees include individual trees as well as those occurring in stands, patches and groups within publicly accessible green-spaces. Here the term urban tree relates to a *growth form* rather than to a vegetation type, thus defining the scope of the study.

While the related term 'urban forest' has been excluded from this study (because much urban forest research is beyond the scope of the paper), it is nonetheless useful to differentiate urban trees from urban forests. Escobedo et al. (2011) have defined 'urban forest' as: "the sum of all urban trees, shrubs, lawns, and pervious soils located in highly altered and extremely complex ecosystems where humans are the main drivers of their types, amounts, and distribution". Their definition conceptualises urban forest as a *vegetation type*. Following Randrup et al. (2005), this paper conceptualises urban trees as a subset of urban forests, because urban forests are not just the sum of urban trees, but include shrubs and grass too (Fig. 1).

While James et al. (2009) have defined green-space as: "unsealed, permeable and soft surfaces such as soil, grass, shrubs, trees and water", this definition is simultaneously too broad and too restrictive for this paper. Green-space in this study is a term referring to: "parks, sporting fields, bushland, [riparian areas of] creeks, rivers and bays, plazas, community gardens, bikeways and paths, ... as well as attractive and safe streets and 'green' links between these various elements ... [and may include] communal space around apartment buildings [as well as] cemeteries, rock walls, street verges and medians, school grounds, rooftop parks, and storm-water channels, and [unpaved] parking lots and open-air, publicly accessible shopping malls" (Byrne et al., 2010) and also includes street trees. Green-spaces also encompass golf courses, botanic gardens, greenways, and utility easements (Vesely, 2007; Young, 2010). Following Tratalos et al. (2007), this review is specifically limited to publicly accessible green-spaces and does not include private gardens, yards, or private campuses.

The well-established ecosystem services literature (Costanza and Farber, 2002; Chee, 2004; Zhao et al., 2009; Liu et al., 2010; Pittman and McCormick, 2010; Sagoff, 2011; Seppelt et al., 2011) includes many studies on the *benefits* of urban trees. Much of this literature stems from ecological economics (De Groot et al., 2002; Farber et al., 2002; Howarth and Farber, 2002; Kumar and Kumar, 2008; Sagoff, 2011) and conservation biology (Brown et al., 2007; Wallace, 2007). But environmental economics and environmental science have also examined this topic in some detail (Sundar, 2005; Daily et al., 2009; Zhao et al., 2009; Dick et al., 2011; Oikonomou et al., 2011).

Urban trees confer a wide range of benefits on city-dwellers. However, scholars from various disciplines have defined the concepts of 'tree benefits' and 'tree services' differently (Tyrväinen and Väänänen, 2005). The urban forest and pollution literature, for example, has focused on the functional effects of urban forest ecosystem structure (McPherson et al., 1998; Nowak and Dwyer, 2000; Nowak et al., 2006; Cavanagh et al., 2009), whereas the economic, ecological, environmental, and natural resource literatures have tended to directly link ecosystem functions to human benefits (De Groot et al., 2002; Millennium Ecosystem Assessment, 2005; De Groot, 2006; Daily et al., 2009).

Ecological economists distinguish explicitly between *ecosystem functions* and ecosystem *goods and services*. Ecosystem function refers to "the capacity of natural processes and components to provide goods and services that satisfy human needs" and include: *regulation functions* (e.g. life-support), *habitat functions* (space for refuge and reproduction), *productive functions* (energy conversion to biomass); *information functions* (e.g. opportunities for aesthetic experience) and *carrier functions* (e.g. transportation) whereas specific ecosystem products/outputs related to identifiable and measurable human benefits (e.g. goods and services) are defined as *ecosystem services* (De Groot et al., 2002; see also De Groot, 2006; Boyd and Banzhaf, 2007; Kroeger and Casey, 2007 and De Groot et al., 2010). To paraphrase Escobedo et al. (2011), ecosystem services are the "specific results of ecosystem functions or aspects of ecosystems utilised actively or passively, directly or indirectly, to sustain or enhance human and non-human life" (see also Chee, 2004; Brown et al., 2007; Wallace, 2007, and Fisher et al., 2009).

Urban trees provide a range of 'services' for urban residents including: mitigating carbon pollution, improving urban air quality, attenuating storm-water flooding, conserving energy, and reducing noise, among others (Arthur and Martin, 1981; Miller, 1997; Low et al., 2005; Burden, 2006). Urban trees also provide habitat for urban wildlife—a benefit because many urban dwellers enjoy encounters with urban animals (Tzilkowski et al., 1986; Gorman, 2004; Lohr et al., 2004; McPherson et al., 2011). Many of these ecosystem services are ostensibly quantifiable and have been measured using various assessment tools (Longcore et al., 2004; Jim and Chen, 2008; Nowak et al., 2008a; Escobedo et al., 2010). Urban trees also provide diverse social, economic, psychological, medical, and aesthetic benefits (Dwyer et al., 1992; Burden, 2006; Good, 2008), some of which stem from the ecosystem services – but many of which may not be quantifiable (Dwyer et al., 1991).