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Review

Urban forests and pollution mitigation: Analyzing ecosystem services and disservices

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ABSTRACT

The purpose of this paper is to integrate the concepts of ecosystem services and disservices when assessing the efficacy of using urban forests for mitigating pollution. A brief review of the literature identifies some pollution mitigation ecosystem services provided by urban forests. Existing ecosystem services definitions and typologies from the economics and ecological literature are adapted and applied to urban forest management and the concepts of ecosystem disservices from natural and semi-natural systems are discussed. Examples of the urban forest ecosystem services of air quality and carbon dioxide sequestration are used to illustrate issues associated with assessing their efficacy in mitigating urban pollution. Development of urban forest management alternatives that mitigate pollution should consider scale, contexts, heterogeneity, management intensities and other social and economic co-benefits, tradeoffs, and costs affecting stakeholders and urban sustainability goals.

1. Introduction

Literature on urban forests, pollution, and sustainability promotes and advocates the positive contributions of trees in maintaining environmental quality (Beckett et al., 1998; Escobedo et al., 2008; McPherson et al., 1998; Nowak et al., 2006; Yang et al., 2005). In general these studies have led to a normative assertion by environmental managers that any increase in urban forests is desirable and will mitigate pollution problems. However, increasing rates of urbanization, lack of prioritization of tree preservation by city officials, inclusion of trees by decision makers in environmental policies, and a widespread neglect of the costs associated with urban forests call into question the assumption that the net effect of urban forests on environmental quality is always positive.

The purpose of this paper is to critically assess the role of trees in mitigating urban pollution and maintaining quality of life by integrating the concepts of ecosystem services and disservices into urban forest management. Specifically, we develop a connection between the ecosystem services of urban forests and their efficacy in mitigating urban environmental pollution problems. We develop this relationship by first reviewing the literature on urban forests and pollution mitigation. Second, we adapt existing ecosystem services definitions from the economics and ecological literature and apply them to urban forests. Third, using air quality improvement and carbon sequestration by urban forests as examples, we consider the role of context, scale, heterogeneity, and management intensity on the benefits – and costs – of urban forests, and highlight the need to define which ecosystem services and specific pollution problems are relevant given the particular economic, social, and environmental goals of urban sustainability. Finally, we present some methods for valuing the benefits provided by different urban forest management alternatives and considering the costs urban forests impose on communities and individuals living in cities.

Integrating ecosystem services of urban forests into environmental quality strategies makes it possible to identify the type and composition of trees that maximizes people's overall quality of life in a specific city at least cost. This analysis can make explicit the tradeoffs associated with different management strategies, which is necessary for the sustainable management of urban forests and to address urban environmental pollution problems and enhance urban quality of life.

2. Urban forests and ecosystems

Urban forests – or the sum of all urban trees, shrubs, lawns, and pervious soils – are located in highly altered and extremely complex

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ecosystems where humans are the main drivers of their types, amounts, and distribution (Dobbs et al. 2011). Urban areas are characterized by high population densities and a network of non-natural, built-up infrastructure (Sanders, 1984; Williams et al., 2009). High per-capita energy and material consumption patterns and large resource inputs have contributed to increased pollution levels in urban areas and emissions of green house gases and aerosols that contribute to regional and global climate change (Ellis and Ramankutty, 2008; Kroeger, 2010; Nowak and Crane, 2002). Urbanization is driving pollution dynamics and the alteration of the structure and function of natural ecosystems (Sanders, 1984; Tratalos et al., 2007; Williams et al., 2009). In addition, climate affects the structure of an urban forest (Sanders, 1984; Tratalos et al., 2007) as do pollutant types and concentrations (Harris and Manning, 2010).

Ecosystems are spatially and temporally explicit units that include all living organisms, the abiotic environment, and the interactions between the two in a given location (Millennium Ecosystem Assessment, 2005). The structure of – and interactions between – the biotic and abiotic components of urban forests determine forest ecosystem functions, or the flows of energy and matter between the ecosystem's structural components (Brown et al., 2007). These ecosystem functions can be identified using descriptors such as primary productivity and biogeochemical cycles. Studies have modeled the flux, deposition, interception and dispersal of pollutants by trees and have used individual tree allometric and ecosystem process based models to estimate CO_2 sequestration by forests (Beckett et al., 1998; Brack, 2002; Cavanagh et al., 2009; Nowak and Crane, 2002; Yang et al., 2005). We refer to these intermediate effects of forests on pollutants and other environmental processes as *functions*.

Substantial urban forest literature has focused on the effects of urban forest ecosystem structure on functions such as air pollution removal, storm water interception, and tree shading (Cavanagh et al., 2009; Escobedo et al., 2008; Jim and Chen, 2009; McPherson et al., 1998; Nowak and Dwyer, 2000; Nowak et al., 2002, 2006; Yang et al., 2005). The ecological literature generally links ecosystem functions in natural landscapes directly to resulting benefits for human well-being (Daily, 1997; Millennium Ecosystem Assessment, 2005). The Millennium Ecosystem Assessment (2005) for example classifies very generic groups of services that provide particular types of benefits to humans.

The use of ecosystem services as a concept and term is increasing in the urban forest and pollution literature (Bolund and Hunhammar, 1999; Dobbs et al., 2011; Escobedo et al., 2010; Jim and Chen, 2009; McPherson et al., 1998; Nowak and Dwyer, 2000; Nowak et al., 2006; Paoletti, 2009; Price, 2003; Tratalos et al., 2007; Yang et al., 2005; Young, 2010). But, according to recent literature from other environmental and natural resource disciplines, this term is often insufficiently well-defined to provide credible, measurable, and meaningful descriptors to explain the benefits and costs of urban forests to decision makers. Specifically, the disciplines of ecological economics (Boyd and Banzhaf, 2007; Kroeger and Casey, 2007), agricultural economics (Swinton et al., 2007), and conservation biology (Egoh et al., 2007; Fisher et al., 2009; Wallace, 2007) have begun to advance the applicability of this term. Currently, there are several available definitions; hence there is a need to analyze the use of these terms in regards to the use of urban forests for pollution mitigation. Moreover, the use of this term needs to be updated and placed in the appropriate *context* and *scale* given the *heterogeneity* of an urban forest of a specific city. That is what is most relevant to the quality of life in cities (e.g., mitigating pollution) and not strictly what is of importance to environmental managers and researchers.

A shift in urban forest management towards systematically taking into account ecosystem services and disservices, which we will later discuss, can help focus awareness on the importance of urban forests for mitigating pollution. Using the literature and case studies as examples, we put forth that not all urban forests mitigate all pollution problems equally through their ecosystem functions. We also provide suggestions as to how a well-defined approach to urban forest ecosystem services and disservices can inform the design of, and priority-setting among environmental quality management alternatives, with outcomes that improve urban quality of life. Finally, an effort to identify and manage for urban forest ecosystem services can help communities and decision makers become aware of the specific types and importance of such ecosystem services.

3. Ecosystem services and disservices of urban forests

Cities are characterized by multiple actors with different interests and varying perceptions towards trees and pollution (Agbenyega et al., 2009; Lyytimäki and Sipilä, 2009; Popoola and Ajewole, 2001). Nevertheless, the normative assumption in the literature is that in general all trees provide ecosystem services such as pollution removal and thus are desirable. A more nuanced assessment acknowledges that urban forests simultaneously produce multiple and wide ranging ecosystem outputs. Depending on the urban setting (i.e., diversity of ecological processes, individual and social perceptions, demographics, and economic realities), these outputs can be described as ecosystem services or disservices. Ecosystem services have varying importance to humans based on that city's particular urban forest structure and pollution problems. Distinguishing ecosystem functions, services (benefits), and disservices (costs) is not just semantics but important. These concepts are being used increasingly as a way to link ecosystem structure and function to people's quality of life in cities (Bolund and Hunhammar, 1999; Dobbs et al., 2011; Jim and Chen, 2009; Lyytimäki and Sipilä, 2009; Tratalos et al., 2007; Young, 2010).

3.1. Ecosystem services – benefits

Ecosystem services have been defined differently by many authors (Boyd and Banzhaf, 2007; Fisher and Turner, 2008; Fisher et al., 2009), but always are defined with reference to humans (Chan et al., 2006; Tallis and Polasky, 2009). It is this attribute that distinguishes them from ecosystem functions. Ecosystem functions occur whether or not there are any humans who may benefit from them (Tallis and Polasky, 2009). For example, if a tree intercepts air or water borne pollutants, it is an ecosystem function; if that function improves local air and water quality then the air and water quality improvement is the ecosystem service that benefits human's health. Based on this distinction between functions and services, Brown et al. (2007) define ecosystem services as "the specific results of ecosystem functions that either directly sustain or enhance human life." Similarly, Fisher et al. (2009) define ecosystem services as aspects of ecosystems utilized actively or passively, directly or indirectly to produce human well-being. Boyd and Banzhaf (2007) and Kroeger and Casey (2007) narrow the definition further by arguing that only components of nature that are directly enjoyed, consumed or used to produce human well-being should be counted as *final* ecosystem services.

The main purpose of defining ecosystem services is to allow for a systematic and comprehensive accounting for the environmental benefits people receive from nature (Boyd and Banzhaf, 2007; Fisher and Turner, 2008). We also recognize that the most useful definition of ecosystem services in a specific case depends on the goals of the analysis. For our purposes, Boyd and Banzhaf's (2007) and Kroeger and Casey's (2007) definition is the most useful one because it is well-suited to measuring environmental quality and estimating the value of other ecosystem services. Thus, we define *ecosystem services* as the components of urban forests that are directly enjoyed, consumed, or used to produce specific, measurable human benefits.

This does not mean that intermediate ecosystem functions are not important; rather their importance is embodied in the value of the final ecosystem services. For example, tree biomass, an ecosystem service that allows timber production, a benefit, is derived from tree productivity, an ecosystem function; air quality, an ecosystem service that contributes to human health, a benefit, is a result of atmospheric deposition, an ecosystem function; temperature amelioration, an ecosystem service that contributes to human health and comfort and to reduced heating and cooling costs, all benefits, results from tree shade effects on absorbed solar radiation, an ecosystem function. As urban forest structure varies, so do ecosystem functions and services and the resulting benefits (Escobedo and Nowak, 2009; McPherson et al., 1998; Nowak and Dwyer, 2000; Nowak et al., 2002; Yang et al., 2005).

The term ecosystem service is often used to refer to *natural* areas that exist "without" human interference and require no input of labor and capital (Brown et al., 2007). However, since urban forests are found in human-dominated, highly altered ecosystems, we also include the ecosystem services provided by *semi-natural* systems such as street trees and maintained green areas in highly urbanized environments sustained by inputs of human labor and resources.

The reason for this focus on ecosystem services as end-products of nature is also justified by the fact that urbanites value these outcomes, even though most are likely to be unaware – or uninterested in – the intermediate ecosystem functions that support them. For example, people value air quality improvements by urban forests, but do not connect this service with the process of dry deposition of pollutants to leaf surfaces per se, the process often measured in studies of urban forests and air pollution removal (Beckett et al., 1998; Cavanagh et al., 2009; Nowak et al., 2006). Along these lines, we include carbon sequestration by urban forests as an ecosystem service, even though arguably it is an intermediate input to the services provided by a stable climate (McHale et al., 2007; Nowak and Crane, 2002). However, we suggest that it is increasingly considered an ecosystem service by many urban policy makers and the general public (Brack, 2002; Escobedo et al., 2010). Table 1 lists the intermediate ecosystem functions, final ecosystem services, and associated benefits provided by urban forests that contribute to pollution mitigation and urban quality of life.

Given our objectives, we focus our assessment on those ecosystem services that are most relevant to mitigating urban pollution, namely, those produced by an urban forest's "regulation functions" (Table 1) or an ecosystem's capacity to maintain the essential ecological process and life support systems (de Groot et al., 2002; Dobbs et al., 2011). In this paper we focus on the air and climate pollution mitigation ecosystem services provided by human-altered urban forests. However, since pollution mitigation

Table 1
Benefits and associated final ecosystem services provided by urban forest ecosystem structure and functions.

Benefit	Ecosystem service	Intermediate ecosystem function
Information functions		
Outdoor recreation	Provision of natural areas for human use (exercise, cultural, wildlife viewing),	Primary productivity, biodiversity
Residential amenities	Provision of aesthetics, views	Primary productivity
Property value premiums	Habitat and refugia provision for humans and wildlife	Biodiversity, primary productivity
Production functions[a]		
Food harvests (crops; domesticated and wild animals)	Production of grains, fruits, nuts and seeds; water availability	Primary productivity, nutrient cycling, pollination, soil productivity; disease regulation
Wood products	Production of woody biomass	Primary productivity,
Fuel production	Production of woody biomass	Primary productivity
Regulation functions relevant to pollution mitigation		
Cooling/heating cost reduction	Tree shade	Primary productivity
Drinking water provision – avoided treatment costs	Aquifer and surface water quality (nutrient and sediment removal)	Soil quality, nutrient cycling, hydrologic cycle
Drinking water provision – avoided pumping/transport costs	Aquifer and surface water availability and decreased storm water runoff	Soil quality, hydrologic cycle
Damage avoidance – health		
Temperature-related mortality and morbidity	Tree shade and wind reduction, carbon sequestration	Primary productivity
Nutrient, bacterial, toxin-related mortality and morbidity	Drinking water quality	Soils quality; hydrologic cycle, biogeochemical cycling
Air pollution related mortality and morbidity	Air quality improvements (low pollutant levels)	Atmospheric deposition, filtering and interception of pollutants
Extreme weather event-related mortality and morbidity	Natural land cover and soils attenuation of tidal waves, floods, hurricanes through C sequestration	Primary productivity, biogeochemical cycling
Damage avoidance – property		
Built infrastructure repair costs	Storm water reduction; soil infiltration, air quality improvement	Soil quality, hydrologic cycle, atmospheric deposition
Climate mitigation and avoided damages	Attenuation of tidal waves and wind storms, C sequestration	Primary productivity, climate change,
Decreased fertilization use and resulting costs	Erosion control, soil nutrient retention	Primary productivity, biogeochemical cycling, soil quality

[a] These ecosystem services are also referred to as "ecosystem goods". C, Carbon.

is just one of several services provided by urban forests, management also needs to consider other relevant ecosystem services if the goal is to maximize human well-being.

A second suite of ecosystem services derived from ecosystem functions is those that produce highly relevant end-products such as biomass, food, raw materials, energy and other resources (Popoola and Ajewole, 2001; Table 1). These "production function" based ecosystem services (de Groot et al., 2002) are generally associated with the primary productivity of ecosystems. For example, urban trees and green spaces accumulate above and below ground biomass and influence atmospheric CO_2 concentrations through accumulation and loss of this biomass (Brack, 2002; Nowak and Crane, 2002).

Table 1 also provides a set of ecosystem services not usually addressed in studies of urban forests and pollutants but are directly relevant to urban quality of life (Bolund and Hunhammar, 1999; Price, 2003). For example, the aesthetic benefits associated with urban forests and the resulting property value premiums accruing to nearby homes are commonly mentioned as an important ecosystem service in European and North American urban forest literature (Kroeger, 2008; Price, 2003; Tyrväinen et al., 2003). Research by Ulrich (1986) demonstrates that human response to vegetated urban landscapes is linked directly to improved human health and reduced health care costs.

Remnant urban forests in cities also provide refugia and habitats for plants and animals, both common and threatened (Williams et al., 2009). The remaining "natural" habitats in urban areas have been largely transformed through fragmentation, the introduction of non-native species, and alteration of natural forest structure and composition. Due to our definition of ecosystem services and the objectives of this paper, we do not include these functions in Table 1. However, since these novel urban habitats affect biodiversity and change community structure and function, they need to be considered as they will affect the provision of ecosystem services but also may impose costs (Millennium Ecosystem Assessment, 2005; Williams et al., 2009).

3.2. *Ecosystem disservices – costs*

Ecosystem disservices, or costs, negatively affect well-being (Lyytimäki and Sipilä, 2009; Zhang et al., 2007). Consistent with our definition of ecosystem services, ecosystem disservices are also defined as end-products. In addition, as with ecosystem services, the levels of disservices from urban forests often accrue differently to various individuals or communities (Agbenyega et al., 2009; Zhang et al., 2007). For example, one party's aesthetically pleasing, comfort increasing shade tree is another party's source of allergens, leaf litter, and obstructed views. These contrasting perceptions will depend not only on the structure of urban forests but also on the preferences of individuals and the specific pollution problem (Agbenyega et al., 2009). Ecosystem disservices are not exclusively financial but may also take the form of social nuisances and even pollution (Dobbs et al., 2011; Lyytimäki and Sipilä, 2009; McPherson et al., 1998; Nowak and Dwyer, 2000). We group these costs into monetary costs, social nuisances, and environmental pollution (Table 2).

The ecosystem disservices described in Table 2 are often additional costs that cities incur when managing urban forests. For example, increasing the number of urban trees can enhance the provision of ecosystem services such as reducing building energy use through shading (Nowak and Dwyer, 2000). However, they may also cause negative consequences that degrade the quality of life, such as an increase in water use in semi-arid areas (Lyytimäki and Sipilä, 2009) and the release of volatile organic compound (VOCs) emissions that might lead to secondary formation of ground-level ozone (Lyytimäki and Sipilä, 2009; McPherson et al., 1998; Nowak et al., 2002; Paoletti, 2009). Tree plantings for climate change mitigation benefits provide another example of how fully accounting for ecosystem services and disservices can turn a perceived benefit into a net cost (Nowak et al., 2002). Specifically, trees can be net CO_2 emitters over their life cycle by accounting for all energy and fuel inputs, pollutant emissions from planting nursery-grown trees, as well as accounting for mulching, watering, fertilization, pruning, removal, and disposal maintenance activities that use fossil fuel burning equipment (Jo and McPherson, 1995; Nowak et al., 2002). Nevertheless, often the social benefits provided by urban forests outweigh the environmental and economic costs of maintaining them (Dobbs et al., 2011). This confusion among the terms ecosystem functions, services, and disservices makes consistent measurement and valuation difficult and has likely limited their usefulness and relevance if a societal goal is to manage urban forests for mitigation of pollution.

Table 2
Examples of costs and associated ecosystem disservices of urban forests.

Costs	Ecosystem disservices
Financial (land, labor, and capital)	Pruning, planting, replacement, removal, transplants, pest-disease control, irrigation Vegetation damage to urban infrastructure: litigation, homes and property, cables, sidewalks, roads Increased humidity – decreased human comfort Foregone land use opportunities Blocked sunlight – increased energy use Green waste – debris, falling tree, branches, litter, Human injuries due to illness, wildlife/insect bites, allergies
Social nuisances	Allergenic pollen and urushiol Refugia for vector-spread diseases: lyme disease, West Nile encephalitis, dengue fever, rabies Attraction of wild animals – damage to structures and ornamental plants, droppings, attacks on pets, annoyance to humans, wild animal bites Obscured views, decreased aesthetics Fear of crime, safety hazards from tree fall
Environmental	Water quantity and quality – fertilizer and pesticide runoff, Soil nutrient inputs – altered nutrient cycles Increased energy consumption from management Air pollution emissions from maintenance activities – carbon and methane from decomposition, air pollutants Volatile organic compound and secondary aerosol emissions Displacement of native species Introduction of invasive species

Adapted from: Lyytimäki and Sipilä (2009) and Nowak and Dwyer (2000).

4. Context, scale, heterogeneity, and management intensity

Fig. 1 illustrates the relationship among ecosystem end-products (i.e., services and disservices) and ecosystem structure and function discussed in the previous sections. This figure delineates a process starting with ecosystem structure as a driver of ecosystem function and the ecosystem services and disservices end-products. The dashed arrows represent these biophysical flows. To differentiate between ecosystem services and disservices it bears reiterating that ecosystem services and disservices are generally measured by their *immediate* importance to an individual's quality of life (Brown et al., 2007). Urban forests, however, are directly and indirectly used by multitudes of actors with different interests who live in close proximity and can act in unison or independent of one another when assigning their relative importance to an ecosystem service.

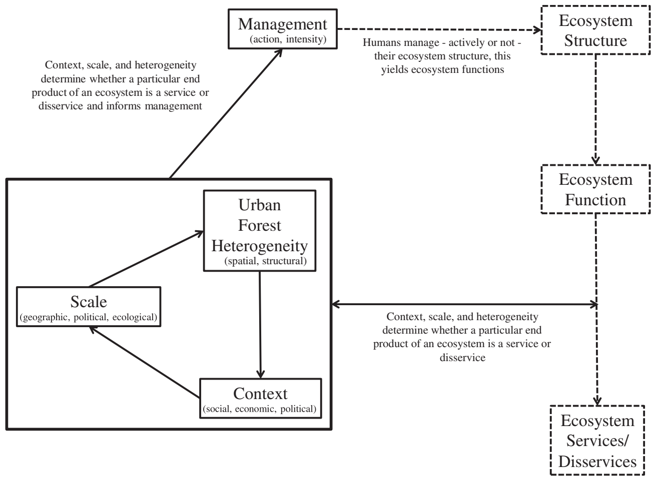

Fig. 1. A framework for analyzing the use of urban forests for pollution mitigation.

Hence, urban forest ecosystem services and disservices are defined by their *relative* importance to quality of life. What constitutes an ecosystem service or disservice, and which ones are most relevant, is determined by a community's given context, scale and heterogeneity of its urban forest. This assessment is illustrated by the double headed arrow in Fig. 1 and also accounts for management intensity. Management is used to manipulate ecosystem structure and thus, the process begins again.

4.1. Scale – context

Context describes the environmental, socio-political, and economic processes and realities that define human and ecological community structure and hence their importance to quality of life (Kremen, 2005; Fisher et al., 2009). Context varies according to locale thus decision makers should not assume that certain ecosystem services are equally important to all urbanites since ecosystem services – and their pollution problems – are location specific (Salzman and Ruhl, 2000; Wagner and Gobster, 2007; Wainger et al., 2001). For example, in Nordic and northern Asian temperate countries shade tree effects and subsequent temperature services that enhance human quality of life might be less important than in subtropical America or Sub-Saharan Africa (Bolund and Hunhammar, 1999; Jim and Chen, 2009; Popoola and Ajewole, 2001). Similarly the air quality improvements brought about by urban forests might be more important in temperate inland cities than in coastal tropical urban areas. Likewise, carbon sequestration by trees is highly valued in most forested regions of the developed world and by policy makers (Escobedo et al., 2010; Zhao et al., 2010). That is not to say that carbon sequestration by urban trees is not important to urbanites living in semi-arid areas but rather other ecosystem services, such as food and fiber production from trees are more important (Popoola and Ajewole, 2001). Thus the relevance of each ecosystem service depends on the *context* of a city's urban forest structure, pollution concerns, politics, climate, and the preferences of its inhabitants.

Scale refers to dimension in space and time of an observation or process and is an indication of magnitude and not a specific value (Lovell et al., 2002). Thus in addition to context, the geographic, political, and ecological scale should be considered when assessing an urban forest's efficacy in improving environmental quality. An appropriate scale is one at which a broad range of ecological, social, and economic issues, interactions, meanings, and emergent properties (i.e. interactions between system structure and function that cannot be understood by studying its individual components in isolation) are present and clearly understood by stakeholders (Cheng and Daniels, 2003; Lovell et al., 2002). The appropriate scale is not fixed but dependent on the given urban context and pollutant. Scale comprises several different dimensions relevant to ecosystem services and disservices from urban forests. At its simplest, scale matters because the size of a treed area generally is positively related to the quantity of ecosystem services provided. For example, air pollution removal, and subsequent air quality improvement, by urban forests generally increases with the amount of leaf area and proximity to pollution source (Cavanagh et al., 2009; Nowak et al., 2006). Similarly, the effects of a tree's VOC emissions on urban ozone problems are minimal compared to the effects of city-wide tree cover (McPherson et al., 1998; Paoletti, 2009). In addition, the production of ecosystem services and disservices is characterized by nonlinearities in the form of threshold effects and emergent properties, with services and disservices requiring a minimum area or particular location in space to occur. Tree VOC emissions for example, may not contribute to local ground-level ozone pollution in a municipality that lacks the other required precursors for ozone to form. However, these emissions may travel regionally outside the municipality to where those precursors are present and thus contribute to ozone formation there (Paoletti, 2009).

Using urban forests to mitigate pollution is likely to be suboptimal or even counterproductive if it does not account for the scale at which possible ecosystem disservices from urban forests affect people. Therefore, managing urban forest ecosystem services for pollution mitigation should consider possible effects across multiple temporal, political, social, economic, ecological, and spatial scales (Millennium Ecosystem Assessment, 2005; Kremen, 2005; Fisher et al., 2009). Such an integrated, comprehensive assessment of the ecosystem services and disservices from urban forests under different management alternatives is complex due to the *heterogeneity* of ecosystem functions and will be discussed in a later section. As a result, the appropriate scale of the analysis can determine the amount of pollution mitigation and drive the amount of ecosystem services and disservices for a given management alternative. While pollution mitigation objectives would suggest that any analysis include the total area in which any relevant ecosystem services or disservices from a management action occurs, political or administrative concerns may lead to different spatial scales of analyses. Such choices, the size of the areas of interest, and tradeoffs should be clearly stated in any analysis.

Even though the importance of scale in managing for ecosystem services has been recognized, there are few cases to date in which the issue of scale actually has been effectively incorporated into the management and valuation of ecosystem services. In fact de Groot et al. (2010) point out that there are apparently no examples of "complete landscape-scale assessments of the quantity, quality and value of an entire bundle of ecosystem services under alternative management regimes" (ICSU et al., 2008, p. 37). Currently, most approaches towards urban forest ecosystem function quantification take an individual tree (e.g. energy use savings) or a broad tree canopy approach (e.g. air quality improvements) when analyzing ecosystem services (McPherson et al., 1998; Nowak and Dwyer, 2000).

Scale and context can also apply to the direct and indirect political and socioeconomic factors that affect trees, ecosystem services, and pollutants in cities (Escobedo and Nowak, 2009; Millennium Ecosystem Assessment, 2005; Wagner and Gobster, 2007). For example, urban trees are found principally on individual landholdings where urban forest structure cannot feasibly be altered by national and regional governments. But, alterations to urban forest structure are being made by thousands of individuals at the scale of their private lots, where a large proportion of urban trees are located (Escobedo et al., 2008). Individually, each decision and tree will have little effect on city-wide air pollution mitigation and other ecosystem services, but collectively, these decisions – and the resulting tree cover – can have measurable effects on urban forest structure and ecosystem services across multiple scales.

4.2. Heterogeneity – management intensity

The other concepts that should be applied when assessing ecosystems services from urban forests are their *heterogeneity* and *management intensity*. Just as pollution concentrations are *heterogeneous* across a city, so too is urban forest structure and the ecosystem services they provide (Escobedo and Nowak, 2009). We refer to *heterogeneity* as spatial and structural differences in urban forest structure and function across an urban landscape.

In cities, urban forest structure and function have been substantially altered by human management, technology and inputs of labor and capital. As a result, ecosystem services provided by urban forests will differ in type and level from those provided by natural ecosystems, which are seen primarily as providing life support services (Brown et al., 2007; Daily, 1997). Additionally conserving and managing urban forests for the provision of ecosystem services is often less financially attractive for landowners than conversion to urban land uses. This lack of financial competitiveness of ecosystem services often is driven by the cost of land conservation; the inability to capture the value of the ecosystem services of their land; and that financial gain from land conversion are often immediate as opposed to the long-term flow of net benefits from conserving urban forests. These causes tend to lead to the displacement in urban areas of bundles of ecosystem services by mostly single-attribute, human-produced substitutes (Farber et al., 2002; Heal, 2000). For example, water treatment plants and engineered storm water structures are utilized to improve water quality and flood control, rather than maintaining pervious surfaces and other natural areas that provide these and many additional ecosystem services.

In general, the less ecosystem structure has been altered, the more self-sustaining this structure is and the less dependent it is on human-produced resource inputs like water, fossil fuels, or fertilizers. For example individual, ornamental trees growing in planting pits along highly urbanized streets require more resource inputs and will generally provide fewer pollution mitigation ecosystems services than trees growing in a protected, naturally forested area in the urban core. We refer to high resource input urban forests as *management intense* since they still provide ecosystem services (e.g. aesthetics) despite inputs of labor, energy, and water required to sustain them. However, since these inputs have pollution impacts themselves, we propose that the fewer resource inputs an urban forest requires to provide the same level of ecosystem functions, the greater the efficacy of its ecosystems services at mitigating pollution and enhancing quality of life.

5. Assessing the efficacy of urban forests in mitigating urban pollution

The dynamics between urban pollution and forests has received attention in this and other journals (Beckett et al., 1998; Harris and Manning, 2010; Paoletti, 2009) and other studies such as McPherson et al. (1998) and Escobedo et al. (2008) have modeled the cost-effectiveness of using urban forests to improve air quality. Heal (2000) discusses that conserving and managing for the ecosystem services of the New York City Catskills watershed was shown to be more cost-effective than construction of water treatment plants. These and many other studies show that methods and models do exist for quantifying urban forest function and ecosystem services and benefits.

5.1. Air quality, carbon sequestration, and urban forests

Studies such as Harris and Manning (2010) and Beckett et al. (1998) have measured individual canopy and trees and pollutant dynamics while Nowak et al. (2006) and Paoletti (2009) have analyzed the role of geographically distinct urban forests and their effects on air pollution problems. Other studies by Brack (2002), Jo and McPherson (1995), Nowak and Crane (2002), McPherson et al. (1998), and Yang et al. (2005) have modeled carbon sequestration by urban forests at local and national scales. Zhao et al. (2010), McHale et al. (2007), and Escobedo et al. (2010) have also analyzed the efficacy of urban forests for offsetting CO_2 emissions. Quantification of function and services by these studies can be used to assess the efficacy of trees in mitigating pollution problems and enhancing quality of life (Escobedo et al., 2008).

To illustrate the integration of urban forests, pollution and ecosystem services, as well as scale, context, heterogeneity, and management intensity in assessing efficacy, we use an example from Escobedo and Nowak (2009) and Escobedo et al. (2008) who modeled the role of urban forests in improving air quality in Santiago, Chile. Although many studies present city-level tree cover and pollution effects, Escobedo and Nowak (2009) found that ecosystem services were heterogeneous in that tree cover (i.e. structure) varied from 12 to 26 percent and particulate matter less than 10 microns in diameter (PM_{10}) concentrations differed from 59 to 84 $\mu g\ m^3$ across the city. Furthermore, function or pollution removal by trees (7.9 g PM_{10}/m^2 tree cover) in lower income areas of the city was similar to shrub removal rates in the high income areas (8.5 g PM_{10}/m^2 shrub cover). Also percent PM_{10} air quality improvement (i.e. ecosystem service) by trees was 1.6 percent in areas with 26 percent tree cover to 6.1 percent in areas of 100 percent tree cover and varied according to socioeconomic strata, season, and pollutant concentration. Despite this, Escobedo et al. (2008) determined that using the cost-effective performance standard defined by the World Bank (1994), managing urban forests for PM_{10} removal in Santiago was just as cost-effective as other PM_{10} reduction technologies and policies (Fig. 2).

Fig. 2 does not imply that urban forests remove the greatest total PM_{10} but rather that at the margin, their cost-effectiveness is within range of other reported technologies and policies. However, unlike these other control approaches, urban forests also provide additional ecosystem services (i.e. bundles). As a result, other ecosystem services and disservices and issues of sustainability need

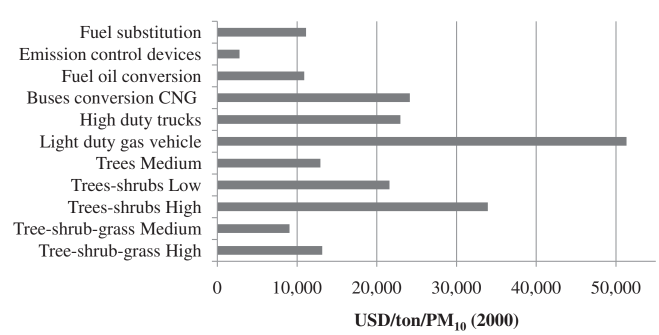

Fig. 2. Cost-Effectiveness in US Dollars (USD) of using trees, shrubs and grassy areas to remove particulate matter less than 10 microns in diameter (PM_{10}) pollution in Santiago, Chile based on Escobedo et al. (2008). High, Medium, and Low represent high, medium and low socioeconomic strata. CNG refers to conversion to compressed natural gas.

to be considered when urban forests are used for mitigating PM_{10}. For example, Santiago is semi-arid and the water needed to maintain areas of high tree cover is limited. Particulate matter problems are also greatest during the winter leaf off season which coincides with greater periods of precipitation; thus rendering trees less effective. Chile is also a developing economy and Santiago has 36 different municipalities and nearly 40 percent of the country's population making planning and management of trees and the space required to grow them extremely complex. So even though using urban forests to mitigate PM_{10} pollution in Santiago is cost-effective, substantially increasing urban forest cover across the city is not sustainable. However, by considering heterogeneity and management intensity, using xeric evergreen trees in strategic localized areas of PM_{10} concern might maximize the ecosystem services in key areas of the city.

Carbon (C) sequestration and its economic value have been quantified by Brack (2002) and others, while McHale et al. (2007) determined street trees to be cost-effective in sequestering C only in areas with high tree growth rates. Zhao et al. (2010) found that C sequestration by urban forests was comparable to C emissions from several industrial sectors in Hangzhou, China (Fig. 3) and offset urban industrial C emission by 18 percent. However, their estimate did not account for residential and transportation C emissions which are increasing in China. A study by Escobedo et al. (2010) did account for all C emission and reduction strategies and found that carbon dioxide (CO_2) sequestration by urban forests was comparable to other CO_2 emission reduction policies (Fig. 4). So, urban forests were just as effective at offsetting annual CO_2 emissions relative to other reduction strategies. But, these same authors and Nowak and Crane (2002) found that urban forests take up a small portion of all annual C emissions and Escobedo et al. (2010) found that additional, city-wide tree plantings would have little effect in offsetting C emissions. Most importantly, none of these studies attempt to fully account for all CO_2 emissions during the life cycle of an urban forests as carried out by Jo and McPherson (1995) and Nowak et al. (2002).

Although using urban forests to mitigate pollution is comparable to other policies in terms of effectiveness, care needs to be taken since the environmental objectives of urban forest strategies can be in conflict with other social and economic objectives such as on-going invasive eradiation projects and equitable distribution of urban tree cover. For example Escobedo et al. (2010) found that 35 percent of total CO_2 sequestration by an urban forest was by undesirable, highly invasive urban trees. To summarize, this and other studies indicate that: 1. There is a need to account for the appropriate scale(s) of analyses (e.g. individual property, city wide, or regional) at which ecosystem services are maximized and ecosystem disservices minimized and context (e.g. climate, socio-political, specific pollutants) when assessing the ecosystem services, disservices and the pollution mitigation potential of urban forests, 2. The management intensity of an urban forest needs to be accounted for since highly maintained parks and street trees might emit more pollution (i.e. CO_2) and use more water than lesser maintained natural areas, 3. Urban forests are heterogeneous and some structures are less preferable than others (e.g., invasive trees), and 4. Given the context and scale of analysis, environmental goals also need to account for other social and economic tradeoffs.

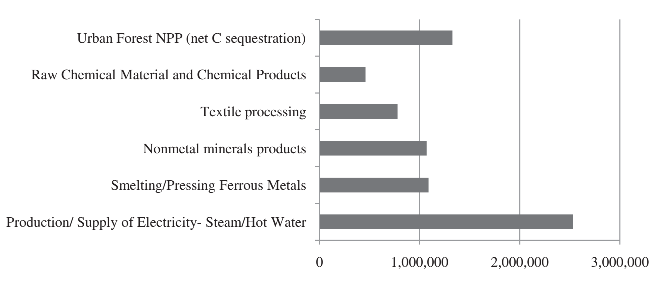

Fig. 3. Urban forest offsets relative to industrial carbon (C) emissions in Hangzhou, China, adapted from Zhao et al. (2010).

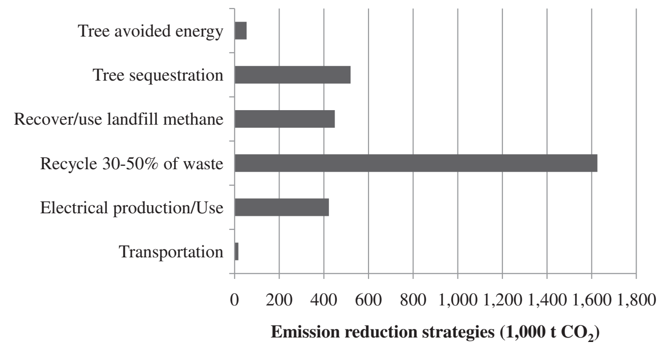

Fig. 4. Comparing urban forest carbon dioxide (CO_2) sequestration to other CO_2 reduction strategies in Miami-Dade, USA, based on Escobedo et al. (2010).

6. Valuing the ecosystem services provided by urban forests

Recent literature suggests that promoting ecosystem services and accounting for ecosystem disservices, as opposed to just quantifying ecosystem functions is more useful to decision makers (Boyd and Banzhaf, 2007; Kroeger and Casey, 2007). Managing for urban forest ecosystem services and disservices at the appropriate scale and context will also make the subsequent benefits and costs more relevant to communities and decision makers – not just researchers and environmental managers (Fig. 2). By having this knowledge, decision makers can weigh the benefits against the costs of urban forest management and policy alternatives allowing for better informed decisions on issues related to urban forests and pollution mitigation (Dobbs et al., 2011; Farber et al., 2002; Heal, 2000; Kroeger and Casey, 2007).

Ecosystem services, by definition, provide value to people. However, as with any good or service, the economic value of a particular ecosystem service in a given context depends on many variables. The economic value of an ecosystem service is defined as its contribution to an individual's quality of life and is determined by their preferences (Agbenyega et al., 2009) and knowledge, their income, as well as other factors. Valuing ecosystem services has the purpose of expressing the different services in a common, usually monetary, metric allowing for comparing tradeoffs and contributions of urban forests to overall human well-being with that of other environmental strategies. The value (i.e., benefits and costs) of an ecosystem service/disservice are reflected in the supply of and the demand for it (Tallis and Polasky, 2009). Unfortunately, supply and demand curves for many ecosystem services are not observable directly as they are not traded in formal markets.

While some ecosystem services are easier to quantify than others, well-established methods are available for estimating the economic value of most ecosystem services (Brown et al., 2007; Farber et al., 2002; Heal, 2000). For example, these methods include but are not limited to revealed preference techniques (e.g., Hedonic Pricing) that estimate an individual's "willingness to pay", stated preference techniques (e.g., contingent valuation method) that estimate an individual's "willingness to pay" or "willingness to accept compensation" (Arrow et al., 1996; Farber et al., 2002; Freeman, 2003), and least-cost or cost-effectiveness techniques. A number of studies have estimated selected ecosystem functions or services and associated monetary benefits of trees in and near cities (McPherson et al., 1998; Heal, 2000; Tyrväinen et al., 2003). Other studies have estimated the economic and societal values of urban forests in the form of benefits such as pleasant landscapes, noise reduction, increased property values, recreational activities and even psychological peace and increased community cohesiveness (Kroeger, 2008; Price, 2003; Tyrväinen et al., 2003). However, few studies present a comprehensive treatment of ecosystem services – as defined in this paper – while also accounting for ecosystem disservices of urban forests (Dobbs et al., 2011; Lyytimäki and Sipilä, 2009). The definition of ecosystem services and disservices advocated in this paper facilitates such a systematic accounting (see Tables 1 and 2 and Fig. 1) as it identifies discrete, well-defined endpoints that can be counted and valued.

Since the values of most ecosystem services vary among different contexts and scales (Salzman and Ruhl, 2000; Wagner and Gobster, 2007), estimating the ecosystem service values for a given city or pollutant is most reliably done through original study. Where an original study is not possible, benefits transfer methods can be used to develop estimates for a particular location that adjust the results from studies done at other locations (Bergstrom and De Civita, 1999; Rosenberger and Loomis, 2003). If accounting for all benefits is not deemed feasible or necessary in a given case, cost-effectiveness analysis or the development of state and performance indicators still allows for the incorporation of some economic considerations while avoiding the complexities associated with benefits valuation (Dobbs et al., 2011; Escobedo et al., 2008; McHale et al., 2007; McPherson et al., 1998). The Millennium Ecosystem Assessment (2005) also presents other methodologies and decision-making frameworks for valuing ecosystem services.

7. Using forests to mitigate urban pollution and enhance quality of life

Unfortunately, urban forest ecosystem services and disservices are reported principally from an academic perspective, but most urban citizens and policy makers do not see the relative value or direct benefits of urban forests in mitigating pollution, while they generally recognize the costs through personal experiences or losses (Agbenyega et al., 2009). People value ecosystem services based – among other things – on the information they have and the perceived importance of particular ecosystem services and pollutant to their quality of life. People's lack of awareness of the overall importance of many ecosystem services combined with an acute awareness of easily perceived and direct ecosystem disservices is another reason why stakeholder involvement, use of science-based information, and deliberative analysis of tradeoffs are key for the decision-making process.

To assess the role and efficacy of urban forests in mitigating pollution we first defined urban forest ecosystem services and disservices as end-products of nature. An ecosystem function was delineated as a service or disservice given the context, scale, and heterogeneity of an urban forest. By focusing on final ecosystem services – as opposed to intermediate ecosystem functions – our approach should facilitate the development of discrete management targets and alternatives that are measurable, achievable, time-bound, and relevant to decision makers. The former characteristics are necessary conditions for monitoring and evaluating environmental quality objectives. By contrast, ecosystem function-based management is likely to lead to decisions that are not as effective and efficient due to the weak correlation between the functions and the actual ecosystem services that directly benefit people's quality of life and mitigate urban pollution. This type of management can actually increase ecosystem disservices and thus leads to losses in urban quality of life.

Given specific pollution problems, associated tradeoffs, scarce resources, and an existing urban forest structure, environmental managers must make a choice among different alternatives by considering the ecosystem services and disservices that are most relevant to decision makers and the urban society at large. These alternatives should describe ecosystem services and disservices, ecosystem structure, and urban sustainability as a continuum; not just an "either/or" decision. An urban forest structure that maximizes pollution mitigation should not necessarily be the one that is implemented, as there may be other goals such as social equity or biological goals that may suggest different types of urban forest structure (Agbenyega et al., 2009; Escobedo et al., 2010; Young, 2010). For example, depending on context, managing urban forests at intermediate scales such as remnant urban woodlots, around schools, hospitals, or neighborhoods can enhance the ecosystem service provision of air quality improvement of PM_{10} more effectively than landscape-scale tree cover (Cavanagh et al., 2009; Escobedo and Nowak, 2009; McPherson et al., 1998) and minimize some ecosystem disservices.

Decisions are often made based on single management objectives which can lead to conflicts among different groups of urbanites. Conversely, managing urban forests according to their context and appropriate scale, relevant urban pollution problems, and overall ecosystem services addresses the basic tenets of urban sustainability – improving the social and economic conditions of increasingly urbanized populations while helping to maintain environmental quality. Citizens also need to be informed of tradeoffs and consequences of their collective decisions on the structure of the urban forests based on the context and scale of their particular urban forest and pollution problems. In addition, by also considering the management intensity and heterogeneity of their urban forest structure, environmental managers and planners can focus on desired ecosystem services that will effectively and efficiently mitigate specific pollutants. Although the link between ecosystem service and pollution mitigation are emphasized in developed countries, they are just as relevant for protecting environmental quality in developing countries (Escobedo et al., 2008; Popoola and Ajewole, 2001; Yang et al., 2005).

Since a key component of managing ecosystem structures for optimization of ecosystem services and pollution mitigation is buy-in by multiple stakeholders; future research in revealed and stated preferences, cost–benefit analyses, quantification of below ground ecosystem functions, urban soil quality, life cycle analyses, and spatial mapping approaches are warranted. This research could be used to better assess the values and tradeoffs among ecosystem services for multiple stakeholders given the context, scale, and heterogeneity of different urban forest management alternatives (de Groot et al., 2010; Tallis and Polasky, 2009; Wagner and Gobster, 2007; Young, 2010). Research efforts are attempting to synthesize the scientific understanding of the relation between ecosystem structure and the resulting services (de Groot et al., 2010) and indicators are being developed that comprehensively describe the interaction between ecosystem functions and services (Dobbs et al., 2011). Models that estimate a range of ecosystem service outputs and their values, some even considering different management alternatives, are also being used and developed (e.g. Urban Forest Effects; Nowak et al., 2006; Artificial Intelligence for Ecosystem Services; http://ariesonline.org/ and de Groot et al., 2010; and Integrated Valuation of Ecosystem Services and Tradeoffs; Tallis and Polasky, 2009). The approach presented in Fig. 1 could be used as a framework for inclusion of stakeholders when applying models and developing urban forest management alternatives for pollution mitigation since management requires public participation in both a policy and scientific process as exemplified by Agbenyega et al. (2009), Young (2010), and Dobbs et al. (2011).

Our ecosystem services/disservices based urban forest management approach can be used to analyze environmental quality objectives that, even in the presence of these uncertainties, are likely to yield superior quality of life results than management that does not explicitly and systematically aim to produce the largest-possible net benefits. Many cities are integrating urban forests as part of urban quality of life and environmental improvement programs and policies. If urban forests can be promoted to policy makers and citizens as means of mitigating pollution within the parameters of urban sustainability, then they can be used to improve human quality of life throughout the cities of the world. We feel this nuanced approach towards urban forest ecosystem services as well-defined end-production of nature – as opposed to those focused on intermediate ecosystem functions – and consideration of ecosystem disservices within a given context, scale, heterogeneity, and management intensity is a first step towards effectively using urban forests for pollution mitigation.

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