Landscape and Urban Planning 99 (2011) 196–206

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

A framework for developing urban forest ecosystem services and goods indicators

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ARTICLE INFO

Article history:
Received 21 June 2010
Received in revised form 25 October 2010
Accepted 4 November 2010
Available online 8 December 2010

Keywords:
Urban ecosystem
Urban soils
Ecosystem services
Disservices
Florida

ABSTRACT

The social and ecological processes impacting on urban forests have been studied at multiple temporal and spatial scales in order to help us quantify, monitor, and value the ecosystem services that benefit people. Few studies have comprehensively analyzed the full suite of ecosystem services, goods (ESG), and ecosystem disservices provided by an urban forest. Indicators, however, are one approach that could be used to better understand the structure of an urban forest, the suite of ESG provided by urban forests, and their influence on human well-being using a simple, innovative and repeatable metric. This study presents a framework for developing indicators using field data, an urban forest functional model, and the literature. Urban tree and soil indicators for groups of ecosystem functions were used to statistically analyze the effects of urban morphology and socioeconomics on urban forest ESG. Findings show that the most influential ESG indicators were tree cover, soil pH, and soil organic matter. Indicators were significantly influenced by land use and time since urbanization, while analyses of property values and household income did not yield any particularly significant results. The indicators presented in this paper present a first approach to non-monetary valuation of urban forest ESG and can be used to develop urban forest structure management goals and to monitor the effects of urban greening policies on human well-being.

1. Introduction

Relative to natural ecosystems, urban ecosystems have been cited as possessing unique climate, soils, vegetation, social dynamics, and flows of energy as a result of different ecological patterns, processes, and disturbances (Alberti, 2009; Pickett et al., 1997; Trepl, 1995). However, other studies such as those of Niemelä (1999), argue that the ecological processes and patterns between urban and other ecosystems are essentially the same, differing only in the importance and prevalence of certain disturbances. If indeed this is the case, urban ecosystems can be studied using common ecological principles (Niemelä, 1999) and other approaches such as the human ecosystem model (Pickett et al., 1997). As such, studying urban ecosystems can elucidate the interactions between social and ecological processes acting at multiple temporal and spatial scales and lead towards a better understanding of the influence of increased population, economic growth, and land use policies on urban forest function, community dynamics, and species distributions (Hostetler and Holling, 2000).

Understanding these functions can in turn improve urban planning, vegetation management, urban sustainability, allocation of financial resources, and most importantly human well-being in cities (Alberti, 2009; Pickett et al., 2009). This study developed indicators of ecosystem services, goods and disservices with the purpose of better understanding ecological processes in urban ecosystems. Most importantly these indicators could assess how the provision of urban forest ecosystem services is influenced by ecosystem structure, urban morphology and socioeconomics. Integrating these indicators into a framework could also be used to monitor the effects or urbanization and policies on urban forests and subsequent human well-being.

1.1. *Ecosystem services and goods*

Ecosystem functions are the physical, chemical and biological processes occurring in ecosystems that are necessary for its self-maintenance (Turner and Chapin, 2005) and are the result of interactions between the biotic and abiotic components of an ecosystem (De Groot et al., 2002). Daily (1997) refers to these functions as ecosystem services and defines them as those conditions and processes through which natural ecosystems, and the species that inhabit them, sustain and fulfill human life. More specifically, ecosystem services are defined by their contribution to human well-being, since they are end products of various ecosystem func-

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doi:10.1016/j.landurbplan.2010.11.004

tions such as climate amelioration and recreation because they are enjoyed, consumed or used by humans. Ecosystem goods, a subset of ecosystem services, can be defined as tangible material products such as wood, fuel, or food that results from ecosystem processes (De Groot et al., 2002).

Other types of ecosystem functions and structures might have negative consequences on human life are referred to as ecosystem disservices (Agbenyega et al., 2008; Lyytimäki and Sipilä, 2009; Zhang et al., 2007) and are exemplified by urban parks that are habitat for rats, mice, vectors and their pathogens (De Stefano and Deblinger, 2005) and human fears related to personal safety in green areas (Jorgensen and Anthopoulou, 2007; Lyytimäki and Sipilä, 2009). Therefore, ecosystem services, disservices and goods are defined by humans who determine their importance and value (De Groot et al., 2002). As a result, differentiating among ecosystem disservices, services or goods will depend on humans, their preferences, and socio-political as well as biophysical contexts (Lyytimäki and Sipilä, 2009; Zhang et al., 2007).

1.2. *Urban forest ecosystem services and goods*

Urban and peri-urban forests as defined in this study are the tree and soil components of an urban ecosystem and are characterized by their structure, amount (e.g. volume), size (e.g. height and diameter), distribution (e.g. covers), and composition (e.g. number of species, soil types). Urban forest structure is a determinant of ecosystem function which has been documented as a means of mitigating environmental quality problems associated with the urban built environment (Nowak et al., 2006). The structure and subsequent function of the urban forest will therefore determine the provision of ecosystem services and goods (ESG; De Groot et al., 2010). Thus, by altering the structure of the urban forest, we can alter certain ecosystem functions that maximize human well-being in cities.

Urban forests, however, can also incur costs due to maintenance and management requirements, contribute to the perceived risk of crime, and emit pollutants (Lyytimäki and Sipila, 2009). Since this could have a negative effect on human well-being, these functions are referred to as disservices and are common to human influenced areas such as urban and ecosystems (Agbenyega et al., 2008; Lyytimäki and Sipilä, 2009; Zhang et al., 2007). For example, highly maintained trees and lawns in cities (e.g. structure) can produce pollen and reduce water infiltration – relative to natural areas – increasing runoff (e.g. functions) which could result in human allergies and flooding events (e.g. ecosystem disservices; Ogren, 2000; Paul and Meyer, 2001). Increased runoff can also decrease water quality by washing off nitrogen and phosphorus excess from fertilizers or increase the concentration of dust particles (Brezonik and Stadelmann, 2002).

1.3. *Urban forest indicators*

Indicators are numerical values that describe the state of a phenomenon or environment and are used as tools to summarize information about the condition of an ecosystem (OECD, 2001; Segnestam, 2002). They reduce dimensionality of data, simplify interpretations, and facilitate communication between experts and non-experts (Segnestam, 2002). Therefore, indicators could be used as metrics for key information concerning ecosystem structure, function and services. Ecological indicators can combine measurable characteristics of structure, such as habitat or landscape patterns, with inherent ecosystem functions and services (Niemi and McDonald, 2004). Conversely, they can oversimplify interactions existing across temporal and spatial scales (Dale and Beyeler, 2001). Furthermore, an indicator does not provide information on the causality behind the value assigned to a particular ecosystem service (Segnestam, 2002). Environmental indicators do, however, condense information about conditions and may show trends and provide a better understanding of the viability of a system (UNEP, 2007). As stated by De Groot et al. (2010), two types of indicators are needed to quantify the capacity of landscapes to provide ESG: (1) State indicators describing which ecosystem function is providing a service and how much and (2) How much of that service can be used in a sustainable way. This information therefore, can provide decision-makers with an evaluation tool for establishing baselines and developing management and maintenance regimes aimed at conserving urban and peri-urban forests (De Groot et al., 2002).

This study developed indicators to assess the state of urban forest ESG and disservices and determine how their provision varied according to urban forest structure, urban morphology, and socioeconomic factors (De Groot et al., 2010; James et al., 2009). The specific hypotheses addressed in this study were to determine if: (1) greater amounts of urban forest cover resulted in increased indicator values of ESGs, (2) affluent areas exhibited higher ESG indicator values, (3) densely populated areas are characterized by lower ESG indicator values, and (4) recently urbanized areas are characterized by lower ESG indicators values. Results can be used as part of a framework that uses indicators to assess the effects of urbanization and policies on urban forest structure and subsequent provision of ESG and disservices.

2. Data and methods

2.1. *Study area*

Gainesville has a population of 113 942 inhabitants (U.S. Census Bureau, 2000), is located at approximately 29°39′N and 82°20′W in North Central Florida and covers an area of 127 km^2. The climate is humid, subtropical with average monthly temperature of 19.4 °C in January and 33 °C in June and mean annual precipitation is 1228 mm (Metcalf, 2004). Soils are sandy siliceous, hyperthermic aeric hapludods and plinthic paleaquults (Chirenje et al., 2004) and natural vegetation is temperate evergreen forest characterized by evergreen oaks (*Quercus laurifolia* Michx, *Quercus virginiana* Mill.) and members of the magnolia (*Magnolia grandiflora* L., *Magnolia virginiana* L.) and laurel family (*Cinnamomum camphora* (L.) Sieb; Dobbs, 2009).

Gainesville's population density is 897/km^2 with a predominance of Caucasians (67% of the total population), followed by African–Americans (24%). The remaining percentage is composed mainly of people of Asian and Hispanic ancestry. Eighty eight percent of the population – 25 years old and older – had completed high school and of those, 42.0% had completed a 4 years university or higher degree. The average family is 2.9 people and average household size is 2.16. Labor force is 55,768 habitants with a per capita income of US$19,122 and annual household income of US$34,327. Properties averaged 30 years since they were urbanized with only a few being over 100 years old (Dobbs, 2009).

2.2. *Field sampling*

Following field methods outlined by Dobbs (2009) and Nowak et al. (2000), 98 simple, random 400 m^2 plots were established inside the city limits during 2005 and 2006 (Fig. 1). Studies of urban forest structure and function frequently use 200, 400 m^2 plots per study area and have yielded different variances for different cities (Escobedo et al., 2010). However, this size study area and sample plots have been used in Florida and determined to be sufficient to address the objectives of this study (Escobedo et al., 2010). Plot measurements included percent tree and shrub cover, plantable space, and surface covers. Diameter at Breast Height (DBH; 1.37 m

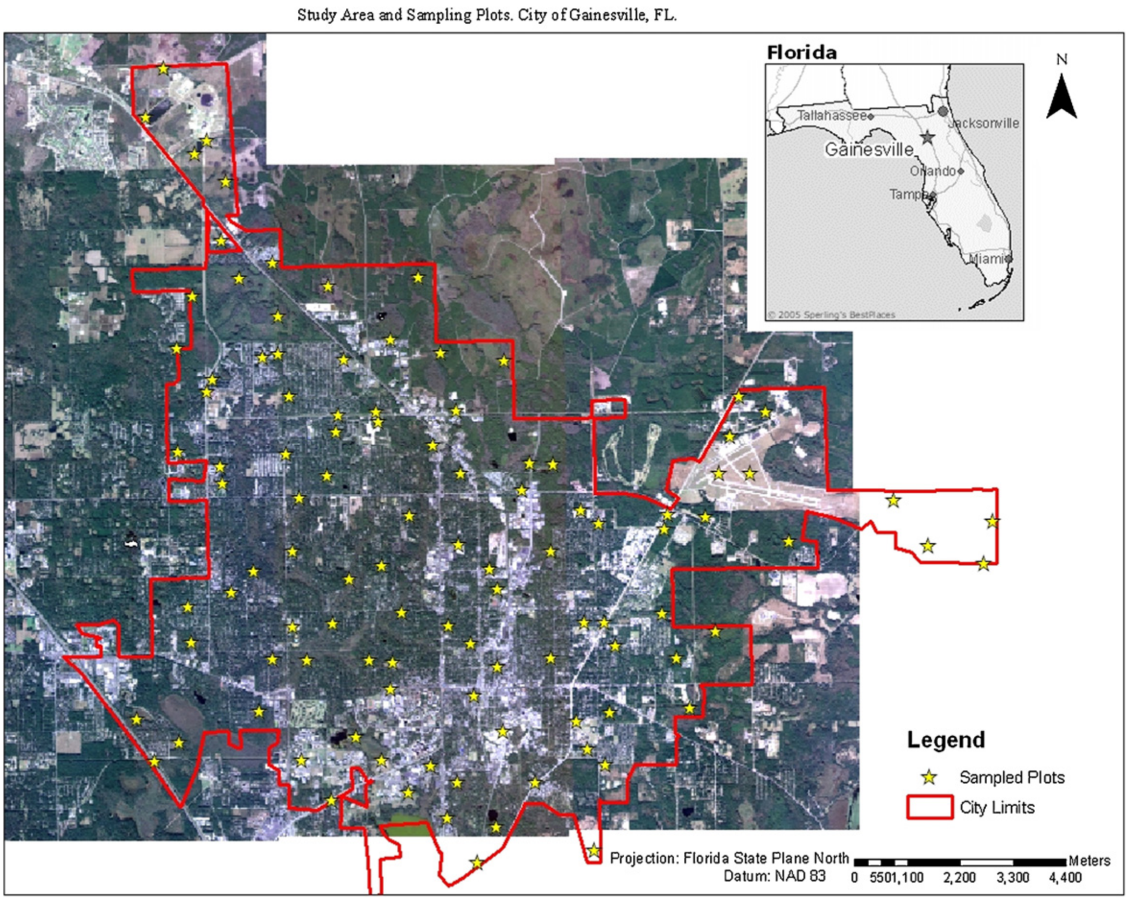

Fig. 1. Study area and sampling plot locations in the city of Gainesville, Florida.

above surface) was measured for every tree on the plot as well as its location and direction relative to plot center. Total height, crown height, crown diameter, percent canopy dieback as a surrogate for condition, percent canopy missing, and crown light exposure for every tree were also measured for every tree on the plot following Dobbs (2009) methods. Sample plots were aggregated into residential, forested, commercial/industrial and institutional categories, according to existing classification used in the City of Gainesville.

Seventy eight of the 98 plots were sampled for soils. Excluded plots had: (a) no permission granted, (b) most of the plot covered by impervious surface or (c) soils too wet to sample. Subplots of 3.1 m^2 were located in the center of each sampled plot following Pouyat et al.'s (2007) protocol for collecting urban soil samples. According to these authors, this sized subplot captures the soil variability existing in the vegetation plot and corresponds to about 1% of the total plot area. Each soil subplot was divided into thirds along three directions at 90°, 125° and 270° relative to plot center and at 1.0 m distance along these directions, samples for soil physical property analyses were collected using three, 5.0 cm × 4.5 cm deep soil tins. One composite soil sample for chemical analysis was also obtained per subplot using a sample probe and 15 random soil cores from the upper 10 cm of the soil surface.

2.3. Tree and soil analyses

Field tree data were analyzed using the UFORE (Urban Forest Effects) model to calculate specific urban forest structure variables (e.g. composition, tree density, tree condition, species richness as well as leaf area and biomass). These same variables were incorporated in the UFORE model along with local hourly meteorological and pollution concentration data to quantify urban forest ecosystem functions (Nowak et al., 2000). The UFORE model was used to estimate hourly dry deposition of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter less than 10 μm (PM10) to tree leaf surfaces. The model also calculated volatile organic compound (VOC) emissions that contribute to ozone and CO formation (Nowak et al., 2000). Tree measurements were also used in UFORE to estimate tree allergenicity and above-ground carbon storage and sequestration as outlined in Escobedo et al. (2010).

Soil bulk density samples were weighed to obtain the volumetric water content and oven dried at 105 °C for 48 h to obtain dry weight. The weight of the inert and organic material greater than 2 mm was removed and discounted from the volume of the sample to obtain total soil volume. The composite samples were air dried and sieved with a stainless steel 2 mm mesh sieve, and sent to the University of Florida Soils Laboratory for chemical analysis. The analysis included Total Kjeldahl Nitrogen (TKN), extractable phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), copper (Cu), sodium (Na), zinc (Zn) and concentrations of lead (Pb), cadmium (Cd), nickel (Ni), as well as organic matter content and pH. Specific laboratory analytical methods are outlined in Dobbs (2009).

2.4. Indicators of ecosystem service and goods

Quantifying ecosystem services in urban areas is complex due to issues presented in the introduction. However, existing ecosystem service typologies and the UFORE model can provide a means towards understanding some key biophysical links between urban forests and ecosystem services. The urban forest ESG indicators were based on De Groot et al.'s (2002) four ecosystem function groups relevant to well-being: regulation, habitat, information and production. Regulation function is defined by maintenance of life support systems and essential processes. The habitat function is defined by the provision of living space and maintenance of biological and genetic diversity. The production function includes the provision of biomass, food and raw materials, while the information function includes services such as spiritual enrichment, mental development and leisure (De Groot et al., 2002). Additionally "ecosystem disservices" were included as an indicator. A group indicator value represents the mean of the ESG that are included in each of the four functional groups. The ESG selected for this study encompass ecosystem structure and functional components that are reported in the literature to affect well-being. In this study human well-being is understood as the conjunction of the suite of material security, personal freedoms, good social relationships and physical health attributes (Millennium Ecosystem Assessment, 2005; Tzoulas et al., 2007).

Regulation functions included several services related to the improvement of well-being in urban areas. Maintenance of air quality service includes decreased air pollution and reduction of ambient temperatures (Whitford et al., 2001). Another contribution to well-being is the removal of air pollutants by trees, since decreased O_3, SO_2 and NO_2 decreases asthma attacks, cancer, risk of cardiac events and respiratory diseases (Bernstein et al., 2004; Sunyer et al., 2003). The maintenance of favorable climate service will reduce heat and energy use for warming and cooling buildings (Simpson and McPherson, 1996), and heat strokes and a general increase in human comfort (Fukuoka, 1997). Storm protection will reduce risks of tree fall and damage to life and property and less tree debris production that will decrease post-storm clean up and removal costs (Escobedo et al., 2009).

The service of drainage decreases runoff, flooding events and wash off of fertilizers and dust particles (Brezonik and Stadelmann, 2002) and prevents the accumulation of excess nutrients and heavy metals on ponds and lakes (Konijnendijk et al., 2005). The maintenance of soil quality results in decreased fertilizer use and reduced investment of soil management. The maintenance of healthy soils could prevent detrimental effects of heavy metals to human health. The filtering of dust particles could reduce the risk of lung diseases (Bernstein et al., 2004) and finally noise reduction decreases human discomfort and hearing problems (Konijnendijk et al., 2005).

The habitat function is related to biodiversity, which maintains all ecosystem functions and supplies genetic and biochemical resources, including crops and pharmaceutical products (Millennium Ecosystem Assessment, 2005; Tzoulas et al., 2007). The production function refers to the potential supply of biomass for bioenergy and compost, therefore if less biomass is produced, less greenwaste is generated and fewer waste management expenses.

The information function relates to aesthetics-based opportunities for recreation and pleasure. Ecosystems provide unlimited opportunities, inspirational and educational fulfillment, reflection and spiritual enrichment (De Groot et al., 2002; Kim and Kaplan, 2004; Tzoulas et al., 2007) and are one of the highest valued ecosystem functions in cities (Konijnendijk et al., 2005; Millennium Ecosystem Assessment, 2005). Aesthetics in this study refers to the preference of people to live in pleasant environments and is revealed in real estate prices (Tyrväinen and Miettinen, 2000). The presence of a tree is also valued by people, so if a tree is lost, monetary compensation is necessary (Nowak et al., 2002).

Disservices imply a reduction in well-being, so fruit fall from trees increases damage to infrastructure and property; thus more effort is needed for litter clean up, or the amount of pollen and allergenic tree structures, produce allergens which decrease well-being (Bernstein et al., 2004). Trees in poor condition can damage infrastructure or injure humans due to falling trees and branches during a disturbing event (Escobedo et al., 2009). Specific methods for quantifying each service, good, and disservices is listed by functional group and summarized in Table 1. Because of data availability and other parallel studies, the regulation function indicator was developed in more detail. However, is acknowledged that quantifying the relationship between the urban forest and human well-being in terms of psychological and social values is critical in assessing ESG.

Using Lun et al.'s (2006) ranking methods, functional groups were subjectively ranked according to UFORE model output, direct measurements, or a combination of measurements and the literature (Table 1). The indicators were subjective in that values were considered either "good" or "bad" with respect to well-being in the study area according to the literature and recommendations on maximum and minimum values for these services (Dobbs, 2009; Table 1). The ranking was based on how the value for each service will increase, decrease, or maintain well-being. Consequently, projecting the indicator values of this study to one scale and grouping the ESG according to De Groot' et al. (2002) ecosystem functions reduced the error associated with multi-scale attributes and facilitated analyses of mixed data.

Plots with no indicator value, those in the lower percentile value for each service, or plots under the recommended values in the literature were ranked as low and assigned a number 1. A moderate provision of ESG was ranked as medium, corresponding to middle percentiles for the indicator values and assigned a number 2. A high provision of ESG was ranked as high and labeled with a number 3, which corresponded to ecosystem service values over the recommended thresholds or in the highest percentile distribution. Categories for ecosystem disservices were ranked using the number 1 for low ecosystem disservices value and 3 for higher ecosystem disservices values. For example, a high ecosystem disservices indicator value might be due to the abundance of trees in poor condition which can result in damage to property during a windstorm, thus decreasing well-being.

Even though some of the indicators are compliments or substitutes, no weighting schemes were used since any information on the value that people might assign to each service, good, or disservice was beyond the scope of this study. The ESG indicator values were however, based on measurements and analyses at the plot level. Scale differences were accounted for by using data at different scales ranging from square meters (e.g. leaf area) to square kilometers (e.g. soil types). Multi-scale studies have been done for vegetation and soil analyses (Anderson et al., 2007; Katul et al., 2001; Yemefack et al., 2005). This approach should also account for different sources of variations common to urban ecosystem. Rankings were used to standardize the indicators, group the ESG by functions, and to make the variables comparable.

2.5. Urban ESG indicator analyses

The indicators were analyzed to explore the effect of socioeconomics, urban morphology, and urban forest structure on the provision of ESG and disservices. Significant differences among the ESG indicators were tested using categories of property value, time since urban development, land use, population density, and household income for each plot using analyses of variance (ANOVA). Property values and time since urban development were obtained from the Alachua County Property Appraisal. Naturally forested areas and tree plantations were assigned 0 years since urban development. Land uses were based on Alachua County categories and were classified as forested, residential, institutional which included parks, commercial including industrial sites and vacant. Population density analyses used four categories based on population quartiles (U.S. Census Bureau, 2000). Sample plots were separated by house-

Table 1
Methods for quantifying ecosystem services, goods and disservices in Gainesville, Florida.

Service	Indicator	Method
Maintenance of air quality	CO_2 sequestration by trees[a]	Carbon is multiplied by 3.67 to convert to CO_2
	Air pollutant removal[a]	Ozone, CO, SO_2 and NO_2 removal multiplied by plot measured tree cover in tons yr^{-1}
Maintenance of favorable climate	Temperature reduction[a]	Temperature reduction effect by tree cover in each land multiplied by m^2 of plot trees cover in °C
Storm protection	Tree structure[c]	Plot tree density and % cover. High tree densities and less than 30% of tree cover produce lower amounts of debris (Escobedo et al., 2009)
	Crown dieback[b]	Average percent individual tree crown dieback for trees on plot
Drainage	Curve number[b]	Curve number (Engel et al., 2004) based on soil hydrologic group and land use
	Soil infiltration[b]	Infiltration curve using Friedman et al. (2001) methods for urban areas using plot soil bulk densities in cm/h
Maintenance of soil quality	Soil fertility[b]	Percent soil organic matter and pH in the sampling plots relative to Craul (1999)
	Soil bulk density[b]	Plot soil bulk density in g cm^{-3} compared to recommendations from Mullins (1991) and Craul (1999)
Maintenance of healthy soils	Soil nutrients[b]	P, K, Mg and Ca in mg kg^{-1} compared to recommendations from Heckman (2006) and Roa et al. (2008)
	Heavy metals[b]	Soil Zn, Cu, Ni and Pb in mg kg^{-1} compared to recommendations for recreational areas (Thornton, 1991)
Filtering dust particles	Pm_{10} removal[a]	Removal by tree cover (m^2) for the city and multiplied by plot tree cover (tons yr^{-1})
Noise reduction	Leaf area[a] and distance to roads[b]	Calculated by weighting distance to roads by leaf area (Nowak et al., 2000) in m^2 per m
	Type of foliage[a]	Percent evergreen species in the sampling unit (Aylor, 1972)
Maintenance of biological and genetic diversity	Shannon diversity and evenness index[a]	Calculated using the formula $SD = -\sum_{i=1}^{s} p_i \ln p_i$, where p_i is the amount of tree species on the plot in relation to the total tree species in the city. A value of 1 means that existing tree species are equally abundant in the sampling unit; a value of zero implies that individuals are concentrated among few tree species
	Ratio of native trees[b]	Percent native trees in the plot, a high percent was assumed to be optimal
Productivity	Tree biomass[a]	Carbon multiplied by 2 to convert to fresh weight biomass. Leaf fall was estimated from leaf biomass estimations and annual leaf fall from Nowak et al. (2000)
Recreation	[c]	Percent tree and maintained grass cover in forest, residential and institutional and recreation land uses according to Bjerke et al. (2006), Kuo et al. (1998) and Parsons (1995)
Aesthetic	[c]	Replacement value includes tree species, condition, size and location per plot (Nowak et al., 2002). Real estate value obtained from Alachua County Appraisal. Trees increase property value by 3–5% (Anderson and Cordell, 1988)
Disservice	Fruit fall[c]	Percentage of trees yielding fleshy fruit; fruit type is based on Gilman's (2007) classifications
	Allergenicity[a]	Based on tree species, leaf biomass and Ogren Plant Allergy Scale (OPALS) ranking scale (Ogren, 2000)
	Damage to infrastructure and risk to human safety[c]	Tree species susceptible to damage in % according to Gilman's (2007) classification
	Decrease in air quality[a]	Ozone, CO_2, and VOC tree emissions; CO_2 emission by tree pruning and lawn mowing; VOC and NO_2 emission by use of leaf blowers in tons yr^{-1}

[a] Estimated using the Urban Forest Effects model.
[b] Measured.
[c] Measured and classified using the cited literature.

hold income categories based on these quartiles and census block data.

3. Results

3.1. Regulation function indicator

Regulation function values are shown in Table 2. Maintenance of soil productivity was high since soil bulk density and organic matter were appropriate for plant growth and phosphorus and calcium were within recommended ranges for Florida (Gilliand, 1976) and the United States (Craul, 1999; Shacklette and Boerngen, 1984). However, high nutrient contents could lead to decrease water quality in lakes and water resources thus detrimentally affecting well-being (Carpenter et al., 1998).

Overall low indicator values were exhibited for properties between 20 and 60 years. Plots in natural and other areas with little urbanization also had high indicator values. Affluent areas had lower indicator values for all ESG, while soil related ecosystem services had higher indicator values. Low indicator values for ESG related to structure could be due to lower tree densities and younger, open grown trees, since affluent areas were generally recently urbanized (Table 3).

3.2. Habitat and production function

More than 75% of tree species were native (e.g. endemic to Florida before 1492 A.D.; Table 2), despite cities usually having increased non-native diversity as a result of introduced species (Zipperer, 2000). However, Gainesville maintained high native tree species diversity despite no apparent trends when analyzed by socioeconomics. The green waste biomass indicator might imply a greater potential for increased yields of green waste and subsequent maintenance needs (Table 2). With the exception of ground litter biomass, the overall production function did not show significant differences in the provision of ESG (Table 4). Indicator values for ground litter biomass varied from medium to low and indicator values classified as medium in forested areas were related to the presence of pine plantation and natural pine forests with lower amounts of litter (Table 6).

Table 2
Descriptive statistics for ecosystem service, goods and disservices indicators using De Groot et al.'s (2002) function groups for Gainesville, Florida.

Function	Service, goods or disservice	Mean indicator	Variance	Min value	Max value	*p*-value
Regulation function	Maint. of good air quality	2.0	0.25	1	2.7	<0.010
	Maint. of favorable climate	2.2	0.66	1	3	<0.010
	Maint. of healthy soils	2.6	0.12	1.6	3	<0.010
	Maint. of soil productivity	2.2	0.19	1.4	2.8	<0.010
	Storm protection	2.3	0.33	1	3	<0.010
	Filtering of dust particles	1.8	0.77	1	3	<0.010
	Noise reduction	2.2	0.30	1	3	<0.010
	Drainage	2.2	0.06	2	2.5	<0.010
	Totals	2.2	0.1	1.5	2.8	<0.010
Habitat function	SI	1.1	0.12	1	2	<0.0001
	RN	2.5	0.54	1	3	<0.0001
	Totals	1.6	0.11	1	2.3	<0.0001
Production function	TB	1.7	0.36	1	3	<0.010
	GB	2.6	0.34	1	3	<0.010
	DTB	2.6	0.54	1	3	<0.010
	GW	1.6	0.61	1	3	<0.010
	Totals	2.1	0.09	1.25	2.5	<0.010
Information function	REC	2.3	0.33	1	3	<0.0001
	AES	2	0.25	1	3	<0.0001
	Totals	2.1	0.16	1	3	<0.0001
Disservices	FF	1.5	0.4	1	3	<0.0001
	AL	2	0	2	2	<0.0001
	DI	1.8	0.73	1	3	<0.0001
	DAQ	2.2	0.21	1	2.9	<0.0001
	Totals	1.9	0.09	1	2.6	<0.0001

Maint, maintenance; Min, minimum value; Max, maximum value; SI, Shannon's diversity index; RN, ratio of native tree species; TB, tree biomass; GB, ground litter biomass; DTB, dead tree biomass; GW, green waste biomass; REC, recreation; AES, aesthetics; FF, fruit fall; AL, allergenicity; DI, damage to infrastructure or humans; DAQ, decrease of air quality; *p*-values are for normality tests.

Table 3
Analyses of variance of socioeconomic variables as predictor and ecosystem services indicators as response variables using De Groot et al.'s (2002) regulation function for Gainesville, Florida ($\alpha = 0.05$).

		AQ	*C*	HS	SP	STO	DUST	NOI	DRA	Mean
Years since urban development (years)	0–20	2.1	2.7	2.6	2.0	2.4	2.2	2.3	2.4	2.3
	20–40	1.9	1.9	2.7	2.2	2.3	1.6	2.1	2.2	2.1
	40–60	1.8	1.9	2.6	2.3	2.1	1.5	2.1	2.2	2.0
	>60	2.3	3	2.8	3	2.5	2.5	3	2.3	2.6
	p-value	NS	0.001	NS	NS	NS	0.01	NS	NS	0.01
Land use	Forested	2.2	2.8	2.5	1.9	2.5	2.2	2.4	2.4	2.4
	Residential	2.0	1.6	2.8	2.3	2.3	1.5	2.1	2.0	2.1
	Institutional	1.5	2.1	2.9	2.4	1.7	1.4	1.7	2.3	2.0
	Commercial	1.7	2.2	2.8	2.2	2.2	1.6	2.4	2.0	2.1
	Vacant	1.8	3	2.3	2.4	1.7	2.0	1.8	2.3	2.1
	p-value	NS	<0.0001	0.005	0.002	0.003	NS	0.004	<0.001	
Property value (US$/acre)	<12,500	2.1	2.5	2.6	2.0	2.5	2.1	2.4	2.3	2.3
	12,501–210,000	1.9	2.5	2.5	1.9	2.2	2.1	2.2	2.3	2.2
	>210,000	1.9	1.8	2.7	2.8	2.2	1.5	2.2	2.0	2.1
	p-value	NS	0.002	NS	0.0003	NS	NS	NS	0.005	NS
Population density (People/US census block)	<953	2.0	2.5	2.7	2.2	2.4	2.0	2.4	2.3	2.3
	954–1698	2.0	2.2	2.6	2.2	2.3	1.9	2.4	2.2	2.2
	1699–3503	2.0	2.2	2.5	2.2	2.3	1.8	2.1	2.2	2.1
	>3503	1.8	1.9	2.6	2.1	2.1	1.5	1.9	2.1	2.0
	p-value	NS	NS	NS	NS	NS	NS	0.003	NS	0.003
Mean annual household income (US$)	<21,000	2.1	2.3	2.6	2.1	2.5	2.1	2.3	2.2	2.3
	21,001–32,700	2.0	2.3	2.7	2.1	2.3	2.0	2.4	2.2	2.2
	32,701–44,000	1.9	2.2	2.6	2.2	2.4	1.5	2.2	2.2	2.1
	>44,000	1.9	2.0	2.7	2.3	2.0	1.6	2.0	2.2	2.0
	p-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, no significant differences ($\alpha = 0.05$). REG, regulation function; AQ, maintenance of air quality; *C*, maintenance of climate regulation; HS, maintenance of healthy soils; SP, maintenance of soil productivity; STO, storm protection; DUST, filtering of dust particles; NOI, noise reduction; DRA, soil drainage; *p*-values for t-tests of socioeconomic variables.

Table 4
Analyses of variance of socioeconomic variables as predictor and ecosystem services indicators as response variables using De Groot et al.'s (2002) productivity function for Gainesville, Florida ($\alpha = 0.05$).

		TB	GB	DTB	GW	Mean	St. dev.
Years since urban development (years)	0–20	1.8	2.3	2.5	1.6	2.1	0.33
	20–40	1.6	2.6	2.6	1.7	2.2	0.29
	40–60	1.7	2.8	2.8	1.8	2.3	0.19
	>60	1.5	2	2	1.5	1.8	0.35
	p-value	NS	0.02	NS	NS	NS	
Land use	Forested	1.6	2.8	2.6	1.8	2.2	0.32
	Residential	2	2.2	2	1.3	1.9	0.34
	Institutional	1.3	2.6	2.8	2.4	2.3	0.17
	Commercial	1.6	2.8	3	1.7	2.3	0.11
	Vacant	1.5	3	2.5	2	2.3	0.35
	p-value	0.02	0.004	<0.0001	0.004	<0.0001	
Property value (US$/acre)	<12,500	1.7	2.4	2.3	1.8	2	0.29
	12,501–210,000	1.7	2.6	2.7	1.6	2.2	0.26
	>210,000	1.8	2.7	2.7	1.6	2.2	0.26
	p-value	NS	NS	NS	NS	NS	
Population density (people/US census block)	<953	1.7	2.3	2.6	1.6	2.1	0.37
	954–1698	1.8	2.5	2.6	1.5	2.1	0.26
	1699–3503	1.5	2.6	2.5	1.9	2.1	0.27
	>3503	1.7	2.8	2.5	1.7	2.2	0.29
	p-value	NS	NS	NS	NS	NS	
Mean annual household income (US$)	<21,000	1.4	2.7	2.9	1.9	2.2	0.16
	21,001–32,700	1.7	2.6	2.8	1.6	2.2	0.25
	32,701–44,000	1.9	2.3	2.1	1.4	1.9	0.40
	>44,000	1.8	2.7	2.5	1.8	2.2	0.31
	p-value	NS	NS	0.04	NS	0.03	

NS, no significant differences ($\alpha = 0.05$). TB, total aboveground biomass; GB, ground litter biomass; DTB, dead tree biomass, GW, greenwaste biomass; *p*-values for t-test among means within socioeconomic variables.

3.3. *Information function*

Indicator values for recreation were high in forested and institutional land uses. Aesthetic indicators had lower values on average when compared to recreation (Table 2). Recreation indicators had a value of medium and were higher in residential areas and decreased in industrial and commercial areas. Aesthetic indicator values were greater in residential areas with higher property values (Table 5). The information function had medium indicator values for all plots and the highest values were on residential land uses and the lowest in forested land uses.

3.4. *Ecosystem disservices*

Overall indicator values for ecosystem disservices were medium (Table 2). The highest indicator values were due to decreased air quality from VOCs and CO_2 emissions from trees and related maintenance activities and are a result of greater numbers of high VOC emitting tree species (Nowak et al., 2000). Tree allergenicity had a medium indicator value (e.g. Ogren Plan Allergenicity Scale between 5 and 7, with 10 being the highest, most allergenic value; Ogren, 2000). Indicator values for damage and risk to urban infrastructure were low. High values would have implied a greater probability for trees to cause damage to infrastructure or increased risks to human safety. Analyzing indicators by property values showed that more expensive properties had trees with lower risks of causing damage (Table 6).

4. Discussion

The ESG indicators outlined in this framework present a typology that can be used in urban ecosystems to link urban forest characteristics and their functions to provision of ESG and disservices as well. The indicators quantify these relationships and several of the selected indicators could be used to monitor the sustainable provision of ecosystem services (De Groot et al., 2010).

Gainesville's tree cover was high and well distributed in both urbanized and naturally forested areas within the city. Findings indicate that the most influential urban forest structure variables for the developed ESG indicators were tree cover, soil pH, and soil organic matter. Urban forest structure was also significantly influenced by urban morphology and time since urbanization which in turn might possibly be determined by land use policies and other unknown urban ecosystem variables (Escobedo et al., 2010; Fraser and Kenney, 2000; Kinzig et al., 2005). Socioeconomic analyses did not present any particularly significant results. However our results and indicator values might not be typical of other cities, since Gainesville is characterized by a high percentage of highly educated residents with advanced degrees living in less affluent, less expensive properties (Dobbs, 2009).

4.1. *Regulation function*

Gainesville's higher tree cover, in relation to other US cities (Nowak et al., 2006), might be resulting in temperatures that are lower than other urbanized areas, since trees have been documented to reduce temperatures from 0.5 to 1 °C (Nowak et al., 2000). In hotter areas for example, an increase in tree cover of 10% could reduce urban temperature by 1.4 °C (Konijnendijk et al., 2005). In Phoenix, Arizona a decrease of 0.28 °C was associated with increased vegetation cover (Jenerette et al., 2007). Temperature estimates could be improved by measuring plot-level temperatures or using a micro or meso-scale climate model. Gainesville had low levels of air pollution relative to other US cities (Nowak et al., 2006). Ozone and CO removal estimates in Gainesville were close to values obtained in the nearby Jacksonville while the amount of SO_2

Table 5
Analyses of variance of socioeconomic variables as predictor and ecosystem services indicators as response variables using De Groot et al.'s (2002) information function for Gainesville, Florida ($\alpha = 0.05$).

		REC	AES	Mean	St. dev.
Years since urban development (years)	0–20	2.3	1.8	1.9	0.31
	20–40	2.4	2.2	2.2	0.39
	40–60	2.3	2.2	2.2	0.48
	>60	1.8	2	1.9	0.12
	p-value	NS	NS	NS	
Land use	Forested	2.3	1.8	2	0.39
	Residential	2.5	2.3	2.4	0.31
	Institutional	2.4	1.9	2.1	0.34
	Commercial	1.7	2.1	1.9	0.42
	Vacant	2.5	2	2.2	0
	p-value	0.02	0.002	0.002	
Property value (US$/acre)	<12,500	2.3	1.5	1.8	0.25
	12,501–210,000	2.2	1.9	2	0.27
	>210,000	2.4	2.5	2.4	0.29
	p-value	NS	<0.0001	<0.0001	
Population density (people/US census block)	<953	2.4	2	2.1	0.42
	954–1698	2.4	2.2	2.3	0.30
	1699–3503	2.4	2	2.1	0.34
	>3503	2.1	2	2	0.46
	p-value	NS	NS	NS	
Mean annual household income (US$)	<21,000	2.5	1.9	2.2	0.33
	21,001–32,700	2.4	2.1	2.2	0.36
	32,701–44,000	2.3	1.8	2	0.42
	>44,000	2.1	2.2	2.1	0.45
	p-value	NS	NS	NS	

NS, no significant differences ($\alpha = 0.05$). REC, recreation; AES, aesthetics; *p*-values for t-test among means within socioeconomic variables.

Table 6
Analyses of variance of socioeconomic variables as predictor and ecosystem disservices indicators as response variables for Gainesville, Florida ($\alpha = 0.05$).

		FF	AL	DI	DAQ	Mean	St. dev.
Years since urban development (years)	0–20	1.3	2	1.9	2.3	1.9	0.29
	20–40	1.6	2	1.6	2.2	1.8	0.29
	40–60	1.6	2	1.7	2	1.8	0.30
	>60	1.5	2	2.5	2.7	2.2	0.02
	p-value	NS	na	NS	NS	NS	
Land use	Forested	1.4	2	2	2	1.8	0.33
	Residential	1.7	2	1.6	2.3	1.9	0.27
	Institutional	1.2	2	1.4	2.1	1.7	0.33
	Commercial	1.5	2	2.1	2.2	1.9	0.31
	Vacant	1.5	2	2.5	2.3	2.1	0.04
	p-value	NS	na	NS	NS	NS	
Property value (US$/acre)	<12,500	1.3	2	2.2	2.3	1.9	0.24
	12,501–210,000	1.5	2	2.2	2	1.9	0.24
	>210,000	1.7	2	1.4	1.9	1.8	0.32
	p-value	NS	na	0.002	NS	NS	
Population density (people/census block)	<953	1.4	2	1.7	2.3	1.8	0.26
	954–1698	1.6	2	2	2.3	2	0.28
	1699–3503	1.6	2	1.8	2.1	1.9	0.27
	>3503	1.4	2	1.7	2	1.8	0.33
	p-value	NS	na	NS	NS	NS	
Mean annual household income (US$)	<21,000	1.5	2	1.9	2.2	1.9	0.24
	21,001–32,700	1.5	2	1.9	2.3	1.9	0.25
	32,701–44,000	1.7	2	1.6	2.2	1.9	0.28
	>44,000	1.5	2	1.7	2.1	1.8	0.37
	p-value	NS	na	NS	NS	NS	

NS, no significant differences ($\alpha = 0.05$); na, not applicable; FF, fruit fall; AL, allergenicity index; DI, damage to infrastructure; DAQ, decrease of air quality; *p*-values for t-test among means within socioeconomic variables.

removed in Gainesville was average for the United States according to Nowak et al. (2006). Overall, areas with higher tree cover (e.g. forested and vacant areas) captured more air pollutants and CO_2 (Escobedo et al., 2010; Nowak et al., 2006).

Soil bulk density values were generally appropriate for plant growth and soil organic matter contents were high, probably due to the frequency of densely forest areas. Areas in Gainesville with a longer history of urbanization had better maintenance of healthy soils than recently urbanized areas since they might have been subjected to fertilization for longer periods of time (Scharenbroch et al., 2005). Incorporating soil biological properties in our study could improve the framework by highlighting its importance for the regulation function (Ritz et al., 2009). Social surveys on fertilizer application rates could have provided a better understanding of human influences on nutrient contents.

Dust particle filtration as an ESG is probably not important in Gainesville, since there is little particulate matter pollution. However, in semi-arid areas, PM_{10} can become a problem and therefore this indicator could be of importance (Escobedo and Nowak, 2009). In these areas, calculating this indicator could be improved by factoring in the distance to the source of pollution as well as leaf area density. Conversely, the storm protection service is much more important in Gainesville than in other states since Florida is prone to hurricanes (Lohr et al., 2004). Attention should therefore be given to urban forest management actions that are relevant to cities' specific environmental and social contexts.

4.2. *Habitat and production function*

Older properties and recently urbanized sites had higher tree diversity indices probably related to the presence of ornamental species that are usually non-native. Increased numbers of native species with increasing years since urban development could depend on past homeowner landscaping preferences and possibly cultural background and social history as these can determine vegetation type, structure, and composition (Bjerke et al., 2006; Fraser and Kenney, 2000; Hope et al., 2003; Kinzig et al., 2005). The production of goods is probably not important (Escobedo et al., 2009), but the use of green waste tree material could be used for energy generations and as additional revenues for home owners. Tree waste can be transformed to firewood, chips or mulch, or possibly even turned into larger wood products. Recycling of green waste could also reduce the environmental and economic costs related to landfill disposal (McPherson, 2006), especially after damaging wind storms.

4.3. *Production and information function*

Quantifying ecosystem services related to recreational and aesthetics in urban forests should account for the different types of users in that city (Matsuoka and Kaplan, 2007). This indicator could be improved by collecting information concerning people's preference towards different urban forest structures (Tzoulas et al., 2007). Specifically, the existential and non-use values of urban trees or the value people assign to different urban forest structures could be used and thus better quantify the link between urban forests and well-being.

4.4. *Ecosystem disservices*

Incorporation of ecosystem disservices in this framework can reveal what the inhabitants of a city consider as negatively affecting their well-being. The priority placed on these disservices will depend on the economical and sociological contexts of the city and its environmental priorities. Inland, polluted cities with low hurricanes frequency will probably give more importance to the decrease of air quality than to hurricane damage (Escobedo et al., 2009; Escobedo and Nowak, 2009). Disservices such as hurricane damage by trees, habitat suitability conducive to biological vectors, crime-related fears associated with treed landscapes, and other nuisances should also be considered (Lyytimäki and Sipilä, 2009). By accounting for disservices, management plans could prioritize urban forest structures and functions that minimize disservice and maximize ESG. Further research on other ESG and disservices relevant to subtropical areas such as water use by urban trees and mitigation of hurricane wind damage to buildings by urban trees is warranted.

4.5. *Limitations, implications and future research*

Using the UFORE model in the development of our indicators could be over, or under, estimating indicator values since the model uses equations developed with species from the northern US. Tree species from the southern US have different growth rates therefore, biomass and leaf area estimates and the subsequent provision of ecosystem services are a study limitation. However, since the UFORE model has been used in several cities in North America, South America, Europe, and Asia, model estimates could be used for intercity comparisons. Future analyses should include the use of site-specific algorithms and equations that correspond to the study area's tree species, climate, and socio-political context. Additionally, including the ecosystem services, goods and disservices provided by shrubs and forbs could improve the framework and provide for a better understanding of the full suite of ESG provided by urban ecosystems.

The ESG selected for each function in this framework depends on data availability and are not assumed to represent all of the ESG provided by an urban forest. Data collection in urban areas is complex because of access, time, and budget constraints. However, several cities around the world have existing UFORE model-type data, general soil inventories, and remote sensing data. Furthermore, our findings show that indicators such as tree cover and soil pH could provide an overall metric for the state of several urban forest ESG and disservices. Some ESG presented in this study might be correlated and their overall effect on individual human well-being may differ among individuals.

The indicator values used in the framework should be standardized if applied to cities and contexts different from Gainesville (Saisana et al., 2005). Specifically, the ecosystem service indicators quantified in this study are based on Gainesville-specific urban forest, weather, and pollution data. As a result, the indicator values will change if directly applied to another city since they will vary in size, climate, and populace. As a result, the value that citizens assign different ESG will be likely different. However if this framework is applied elsewhere, indicators can be rescaled using measured data from that specific community and the following equation:

$$\text{Indicator} = \frac{x_{q,c} - \text{mean}(x_q)}{\text{rang}(x_q)} \quad (1)$$

where $x_{q,c}$ is the value of indicator x_q for the city c (Saisana and Tarantola, 2002). The mean will include the average value for the service in city c and the range will encompass the difference between the minimum and maximum value for the ESG in city c. Categorizing functions according to our framework should facilitate its application to other cities by creating a similar scale for different ESG.

5. Conclusion

This study developed a framework and indicators of ESG and disservices provided by urban forests using an existing typology, urban forest field measurements, modeling, and the literature. The framework accounted for ecosystem structure and functions and linked them to well-being. Correlations at the landscape, habitat, and species level as well as multi-scale analyses were also incorporated into the framework. Once urban forest structure data is obtained, the calculation of the indicator is repeatable, easy to compute, and results are presented in simple metrics suitable for managers, citizens, policy makers, and researchers. The indicators present a first approach to non-monetary valuation of ESG and disservices in urban areas (De Groot et al., 2010) and are an alternative to other existing indicators, such as the environmental sustainability index, accounting for other environmental, aesthetic and recreational values at coarser scales.

This study corroborates Whitford et al.'s (2001) and Niemelä's (1999) observations that the ecological state of a city depends heavily on the state of the urban trees and that ecological structure and functions between urban and natural ecosystems are similar. If so, our indicators for urban forest ESG can be used to measure effects of and drivers to human development (UNEP, 2007), demographics, economic development, socio-cultural dynamics and political contexts. The framework and indicators can also be used to monitor and evaluate the effects of urbanization, establish management goals, or analyze the results of urban greening polices on well-being. As noted by one of our reviewers, "Establishing innovative, transferable, simple, and integrative approaches for developing indicators of ecosystem goods and services could inform urban planning and facilitate nature conservation". Indicators could also facilitate interdisciplinary and multidisciplinary research approaches for comparative of urban ecosystems (James et al., 2009). In conclusion indicators, such as the ones presented in our study, should be constantly evaluated since new ecosystem services could be perceived or prioritized. Thus it is important that indicators be flexible since our understanding of ESG and urban ecosystems is constantly evolving.

Acknowledgements

We would like to mention Florida Agricultural Experiment Station and USDA Forest Service Centers for Urban and Interface Forestry for funding. We would like to thanks Mark Hostetler for his careful reviews, Wendell Cropper and Jane Southworth for their valuable intellectual and conceptual input.

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