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Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities

Francisco Escobedo [a,*], *Sebastian Varela* [a], *Min Zhao* [b], *John E. Wagner* [c], *Wayne Zipperer* [d]

[a] *University of Florida-IFAS, School of Forest Resources and Conservation, PO Box 110410, Newins-Ziegler Hall, Gainesville, FL 32611, USA*
[b] *Urban Ecology and Environment Research Center, Shanghai Normal University, Shanghai 200234, China*
[c] *SUNY- College of Environmental Science and Forestry, 304 Bray Hall, Syracuse, NY 13210, USA*
[d] *USDA Forest Service, PO Box 110806, Gainesville, FL 32611, USA*

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ABSTRACT

Urban forest management and policies have been promoted as a tool to mitigate carbon dioxide (CO_2) emissions. This study used existing CO_2 reduction measures from subtropical Miami-Dade and Gainesville, USA and modeled carbon storage and sequestration by trees to analyze policies that use urban forests to offset carbon emissions. Field data were analyzed, modeled, and spatially analyzed to compare CO_2 sequestered by managing urban forests to equivalent amounts of CO_2 emitted in both urban areas. Urban forests in Gainesville have greater tree density, store more carbon and present lower per-tree sequestration rates than Miami-Dade as a result of environmental conditions and urbanization patterns. Areas characterized by natural pine-oak forests, mangroves, and stands of highly invasive trees were most apt at sequestering CO_2. Results indicate that urban tree sequestration offsets CO_2 emissions and, relative to total city-wide emissions, is moderately effective at 3.4 percent and 1.8 percent in Gainesville and Miami-Dade, respectively. Moreover, converting available non-treed areas into urban forests would not increase overall CO_2 emission reductions substantially. Current CO_2 sequestration by trees was comparable to implemented CO_2 reduction policies. However, long-term objectives, multiple ecosystem services, costs, community needs, and preservation of existing forests should be considered when managing trees for climate change mitigation and other ecosystem services.

1. Introduction

As of 2008, 50 percent of the world's population lives in cities and 10 percent of these live in megacities of 10 million or more (UN, 2006). The urban population of the tropics and subtropics is expected to grow to 4 billion by 2025, and major cities are expected to grow substantially in surface area (Avijit, 2002). Cities are consuming increasing amounts of energy and emit much of the world's carbon dioxide (CO_2) as they rapidly urbanize and industrialize. Fossil fuel burning has produced approximately three-quarters of the increase in CO_2 from human activity over the past 20 years and CO_2 emissions due to the burning of fossil fuels continue to increase (Pearson and Palmer, 2000).

Unless measures are taken to mitigate the rising accumulation of atmospheric CO_2, these increases might pose a threat to ecological and socio-economic systems (Karl et al., 1997).

However, reducing atmospheric CO_2 concentration from urban areas poses serious challenges for urban environmental planners and managers. For example, in 1993 Miami-Dade

* *Corresponding author*. Tel.: +1 352 378 2169.
E-mail address: fescobed@ufl.edu (F. Escobedo).
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County unanimously approved "A Long Term CO_2 Emission Reduction Plan for Miami-Dade County" (Hefty et al., 2007). The policy's goal was to reduce urban CO_2 emissions countywide by 20 percent of the 1988 baseline levels by the year 2005. This translated into a goal of reducing emissions in excess of 11 million tons of CO_2 each year during this period. Since that initial policy, urban tree planting and management to mitigate CO_2 emissions have been identified as practical approaches to achieve these policy goals (Hefty et al., 2007; Nowak and Crane, 2002; McPherson and Simpson, 1999).

Urban forests can reduce atmospheric CO_2 levels in three ways. First, through growth urban trees remove atmospheric CO_2 and store it in their biomass (Nowak and Crane, 2002). Several studies have quantified CO_2 storage and sequestration by temperate urban forests (Nowak and Crane, 2002; Jo and McPherson, 1995; McPherson, 1998). Second, urban trees decrease building cooling demand by shading and evapotranspiration, thereby reducing CO_2 emissions associated with fossil fuel use in energy production (McPherson, 1998). Third, other vegetation and soils store organic carbon (Jo, 2002). Urban forests can however also emit CO_2 in the form of tree maintenance related activities, decomposition of green waste, and dying trees. Thus, urban forest structure and composition directly influence carbon sequestration. Urban forest structure and composition in turn are influenced by human and management decisions, such as species selection for public areas and preferences of private property owners (Nowak et al., 2002).

Urban forest structure and composition in subtropical areas are different in terms of growth and decomposition rates from temperate zones and subject to frequent hurricanes and invasive species proliferations (Duryea et al., 2007; Zhao et al., 2010; Jim and Liu, 2001). Furthermore, because of its unique climate, rapid rates of urbanization, geography, and biogeochemical cycles, CO_2 dynamics in subtropical urban forests should be different than northern, temperate areas. However, very little information exists on the potential of subtropical urban forests, such as those of Florida, to offset CO_2 emissions.

Given policy goals of using urban forests for CO_2 offsetting, the main objective of this study is to examine the efficacy of using urban forest to mitigate CO_2 in subtropical cities such as those of Florida. The approach used is novel in two ways. First, we analyze two cities with differing patterns of urbanization from 1980 to present day; one characterized by a high rate of land development which ultimately results in higher CO_2 emissions and the other by lower rates of land development which enables the city to preserve natural forests within its boundaries and also emit less CO_2. Urban forests effects in these two cities can be placed at the two extremes of an urbanization gradient ranging from small, peninsular, inland cities to large, coastal, highly urbanized areas. Second, while the examination includes standard methodologies of urban forest data collection and CO_2 offsetting estimation, we also spatially analyze CO_2 offsetting in two urban areas with different urbanization patterns. This approach will allow us to establish CO_2 stock and sequestration baselines for subtropical urban forests and allow for the comparison of offsets with anthropogenic emissions from cities to assess the efficacy of managing urban forests to mitigate CO_2. This same information can be used to assess the CO_2 sequestration potential of urban forests with other ecosystem services and policy objectives such as shading and mitigation of hurricane damage by trees as well as control of invasive trees and secondary CO_2 emissions due to urban forest maintenances activities.

2. Material and methods

2.1. *Study areas*

The coastal, urbanized portion of Miami-Dade County, Florida defines the study area with a high rate of land development. This study area encompassed 1273 km^2 of Miami-Dade County centered at 25° N and 80° W in southeast Florida. Miami-Dade has a humid, subtropical and tropical climate with a mean annual precipitation of 147 cm and an average maximum and minimum temperature of 28 °C and 20 °C (Winsberg, 2003). Total population increased from 1,937,094 to 2,253,362 inhabitants from 1990 to 2000 and in 2000 population density varied from 2313 to 3891 inhabitants/km^2 in the incorporated cities of Homestead and Miami, respectively (USCB, 2009).

The study area characterized by a lower rate of land development is Gainesville, Florida. This study area is 122 km^2 and is centered at 29° N and 82° W in inland, north-central Florida. The climate is humid, subtropical and is characterized by a mean annual precipitation of 132 cm and an average maximum and minimum temperature of 27 °C and 14 °C (Winsberg, 2003). The total population in Gainesville increased from 84,770 to 95,447 from 1990 to 2000 and population density in 2000 was 762 inhabitants/km^2 (USCB, 2009).

2.2. *Determining efficacy*

The objective of this study is to analyze the efficacy of using urban forests to mitigate CO_2 in subtropical cities. Developing an efficacy standard is difficult due to the nature of the problem; namely, there is no benchmark urban forest that can be used to develop such a standard. While acknowledging this difficulty, a standard is necessary to assess the main objective of this study. To this end we used the following logic to develop a standard. First, mitigating CO_2 in urban areas is not based on a single approach. There are often multiple approaches used in concert to mitigate CO_2. In the case of Miami-Dade County and Gainesville, there were four CO_2 policy reduction strategies used: Transportation, Electrical Production/Use, Solid Waste, and Facility/Operations (e.g. Hefty et al., 2007). Thus the standard should measure the efficacy of urban forests relative to these other commonly used policies in a given study area, policy context, and climate. Second, a measure of central tendency would be tenable as a performance standard. However, given the small number of potential observations and that the relative mitigation rates could be asymmetric and include a zero observation, we used both the arithmetic mean and median to develop upper and lower thresholds as a standard to assess efficacy.

2.2.1. *Interpretation of assessment criteria*

The implication of the arithmetic mean being less than the median is that the relative reductions are distributed asymmetrically with at least one strategy having low relative

Table 1 – Carbon dioxide emission reduction strategies by sector for Gainesville and Miami-Dade (ACEPD, 2001; GRU, 2007; Hefty et al., 2007; Kappelman, 2007).

	Strategies to reduce CO_2 emissions	Gainesville Total emission: 2,097,627 tons of CO_2			Miami-Dade Total emission: 31,967,000 tons of CO_2		
		Emission reduction (tons/ha/yr)	Relative reduction (per approach)	Absolute reduction (of total)	Emission reduction (tons/ha/yr)	Relative reduction (per approach)	Absolute reduction (of total)
Reduction strategies	Transportation	1.3	0.8%	3.2%	0.1	0.1%	0.6%
	Electrical production/Use	31.5	18.3%	77.2%	2.6	1.3%	13.6%
	Solid Waste	0	0%	0%	13.0	6.5%	67.3%
	Facility/operation efficiency	2.2	1.3%	5.4%	0	0%	0%
	Median	1.8	**1.1%**	4.3%	1.4	**0.7%**	7.1%
	Arithmetic mean	8.8	**5.1%**	21.5%	3.9	**2.0%**	20.4%

reduction values. In this case: 1) if the relative efficacy of urban forests to sequester CO_2 is less than the lower threshold, most of the other strategies used in a given study area and context have on average a greater relative efficacy; 2) if the relative efficacy of urban forests to sequester CO_2 is greater than the upper threshold, the relative efficacy of urban forests to sequester CO_2 is grouped with the relative efficacies in the upper half of the strategies used in a given study area and context; and 3) if the relative efficacy of urban forest to sequester CO_2 is between the lower and upper thresholds, urban forests are moderately effective compared to the other strategies used in a given study area and context.

The implication of the arithmetic mean being greater than the median is that the relative reductions are distributed asymmetrically with at least one strategy having high relative reduction values. In this case and for a given study area and context: 1) if the relative efficacy of urban forests to sequester CO_2 is less than the lower threshold, the relative efficacy of urban forests is grouped with the relative efficacies in the lower half of the strategies used; 2) if the relative efficacy of urban forests to sequester CO_2 is greater than the upper threshold, the relative efficacy of urban forest to sequester CO_2 is greater on average than most of the other strategies used; and 3) if the relative efficacy of urban forest to sequester CO_2 is between the lower and upper thresholds, urban forests are moderately effective compared to the other strategies used.

Finally, the implication of the arithmetic mean being equal to the median is that the observations are symmetrically distributed. In this case the lower and upper thresholds are the same and: 1) if the relative efficacy of urban forests to sequester CO_2 is less than this threshold, most of the other approaches used in a given study area and context have a greater relative efficacy; and 2) if the relative efficacy of urban forests to sequester CO_2 is greater than this threshold, most of the other strategies used in a given study area and context have a smaller relative efficacy.

2.2.2. *The assessment criteria*

The alternative strategies formulated to satisfy Miami-Dade's policy goal for CO_2 reductions led to an annual average reduction of 2,532,732 tons of CO_2 (Hefty et al., 2007). There were four CO_2 policy reduction strategies used in these policies and for this analysis: Transportation, Electrical Production/Use, Solid Waste, and Facility/Operations efficiency. Information from Hefty et al. (2007) was used to define Miami-Dade County's CO_2 reduction strategies. Emission sectors and CO_2 reduction strategies for Gainesville were determined using Alachua County Environmental Protection Department (ACEPD) (2001) and Gainesville Regional Utilities (GRU) (2007), Kappelman (2007) data and personal communications with S. McClendon (Alachua County Sustainability Coordinator; May 2009). Transportation sectors for both cities included mass transit and road improvements, increased use of bicycles, increased fuel efficiency, and increased traffic demand management programs. Electrical production/use in Miami-Dade included increased efficiencies of facilities and operations, promotion of participation in energy conservation, expanded use of landscaping and white surfaces. In Gainesville, facility operation/efficiency was analyzed as its own sector. Finally, solid waste in Miami-Dade consisted of recycling of waste streams, recovery and use of methane gas from landfills and waste water treatment sludge. Comparable data for Gainesville was not available. Table 1 defines the CO_2 reductions (tons/ha/yr) for these approaches.

For purposes of assessing relative efficacy, the relative reduction per approach column defines the assessment criteria (Table 1). The observations are asymmetric with at least one strategy having high relative reduction values, thus the arithmetic mean will define the upper threshold and the median will define the lower threshold. For Gainesville the upper and lower thresholds are 5.1 percent and 1.05 percent, respectively. For Miami-Dade the upper and lower thresholds are 2.0 percent and 0.7 percent, respectively.

2.3. *Field data collection and carbon estimation*

During January through May 2008, 229 random 0.04 ha permanent plots were allocated in the urbanized portion of Miami-Dade County, while 93 random 0.04 ha plots were located within the city limits of Gainesville during July 2005 through May 2006. These random plots were located across different land uses (Table 2). Data were collected for each tree and palm on every plot with a minimum diameter at breast height (DBH at 1.37 m above-ground surface) of 2.5 cm, regardless of growth habit. Tree and palm measurements included: species, number of stems, DBH, total height and crown dieback. Distance and direction to residential

Table 2 – Land uses analyzed in Miami-Dade and Gainesville, Florida.

Land use	Miami-Dade			Gainesville		
	Area (ha)	% of the area	Number of plots	Area (ha)	% of the area	Number of plots
Agriculture	22,003	13.6	42	0	0	0
Commercial	5664	3.5	16	0	0	0
Industrial	6431	4.0	4	182	1.5	3
Institutional	5547	3.4	13	720	5.9	7
Park	11,338	7.0	19	271	2.2	4
Residential	40,575	25.1	92	2847	23.4	30
Transportation	25,617	15.9	11	1263	10.4	16
Utility	6135	3.8	6	2977	24.5	3
Vacant	27,395	17.0	20	335	2.8	4
Wetland/Water	10,746	6.7	6	209	1.7	2
Forest	0	0	0	3370	27.7	24
Total	161,450	100	229	12,174	100	93

buildings less than 2 stories high, were measured for trees and palms in the plot that were at least 6 m tall and within 15 m of a residential building. Even aged, dense, pine rockland, mangrove, and *Melaleuca quinquinervia* plots in Miami-Dade were sampled using 0.01 ha subplots following methods outlined in Zhao et al. (2010). Measurements were then multiplied by a factor of 4 for subsequent analyses. Plot surface covers including potential available space for additional medium to large shade trees were also estimated visually.

Field data were used with the Urban Forest Effects (UFORE) model to quantify urban tree carbon storage and sequestration as well as to approximate the effects of tree shading and transpirational cooling on building energy use and subsequent avoided C emissions (Nowak et al., 2002). The UFORE model is an urban forest structural and functional model developed by the USDA Forest Service that is increasingly being used by communities to assess structure, ecosystem services, and value of urban forests. For this study, carbon storage indicates total carbon accumulated over the life of a tree's in-plant biomass and sequestration is annual carbon uptake as a function of tree growth. The UFORE computer model quantifies composition and biomass for each tree using allometric equations from the literature (Nowak and Crane, 2002). Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5. Species-specific, genus or family biomass equation means for forest-grown trees were used to estimate total tree wood biomass and below ground biomass was estimated using a root-to-shoot ratio of 0.26 (Nowak et al., 2002). Urban trees tend to have less above-ground biomass than trees in forests, therefore biomass results for urban trees were adjusted accordingly by reducing biomass estimates by 20 percent (Nowak et al., 2002).

Carbon sequestration was estimated from site-specific field measurements and land use information as well allometric formulae from the literature, mean growth and mortality rates, and decomposition rates incorporated into the model (Nowak et al., 2002). Gross carbon sequestration was estimated from average diameter growth per year for individual trees, land-use types, diameter classes, and DBH from field measurements (Nowak et al., 2002). Adjusting for tree condition, gross carbon sequestration (G_cS), was calculated as the difference in the amount of carbon storage between a measured tree's actual (x) and predicted carbon storage in one year (y) using the equation:

$$G_cS = y - x \quad (1)$$

Net carbon sequestration includes released carbon due to tree death and subsequent decomposition based on actual land use categories, mortality estimates, and tree size and condition (Nowak et al., 2002). Since population carbon estimates are based on individual trees, the model estimated the percent of that measured tree that will die and decompose as opposed to allowing a percentage of the tree population to die and decompose. These individual estimates were aggregated to estimate decomposition for the total population, based on field land use and two types of decomposition rates, rapid and delayed release. This assumes that urban trees release C soon after removal whereas trees in forest or vacant areas are likely left standing for prolonged periods thus delaying release (Nowak et al., 2002). Additional assumptions behind decomposition rates and related C emissions are presented in Nowak et al. (2002).

Net carbon sequestration was then estimated by reducing the amount of carbon sequestered due to tree growth by the amount lost due to mortality (Nowak et al., 2002). Although the UFORE model was developed using mostly data from northern temperate areas, some of the biomass allometric equations were from southeastern US species. Specific species equations used and their provenance are detailed in Nowak et al. (2002). To account for the extended growth periods of subtropical climates, the model uses actual frost free days for Gainesville and Miami-Dade County to adjust default growth rates obtained from temperate areas in the US. This adjustment resulted in growth rates that were within 30 percent of those measured for *Quercus laurifolia* in Gainesville by Spector and Putz (2006). Carbon emissions due to tree maintenance, decomposition of green waste, and downed trees from hurricane impacts are not considered in this analysis. Detailed methods and allometric equations for calculating carbon storage and sequestration are presented in Nowak et al. (2002). Carbon results were multiplied by 3.7 to obtain CO_2 values used in subsequent analyses. Parameters such as species-specific biomass equations, mortality rates, and root-to-shoot ratios can be incorporated into the UFORE model; unfortunately this information is not currently available for trees common to our study areas.

2.3.1. *Avoided carbon dioxide due to shading and climate regulation*

The UFORE model was also used to approximate the effects of urban trees on building energy use due to shading and climate regulation, or carbon avoided as defined by McPherson and Simpson (1999) for use in guidelines for CO_2 reductions through urban forestry. Tree effects on building energy usage and subsequent carbon emissions from power plants in Miami-Dade County and Gainesville were estimated using information from McPherson and Simpson (1999). The amount of carbon avoided from power plants due to tree effects was calculated using the cardinal direction of a tree relative to a building, climate characteristics, leaf type (e.g. deciduous or evergreen) and percent cover of buildings and trees on a plot. Default values established by McPherson and Simpson (1999) for the Gulf Coast region of the US were used for climate and building characteristics and shading and climate energy effects. The effects of tree shading on building energy use, were adjusted according to building vintage types as set by McPherson and Simpson (1999). The effects of individual evergreen or deciduous trees and palms on cooling energy use (*TE*) were adjusted based on actual tree canopy condition (*c*) using formula:

$$TE = 0.5 + (0.5 \cdot c) = 0.5 \cdot (1 + c) \tag{2}$$

where $c = 1 - \%$ crown dieback as measured in the field.

Total tree cover effects on local climate estimates were based on plot building and tree cover, tree condition, and procedures from McPherson and Simpson's (1999) Gulf Coast United States region values and formulas relating tree cover effects on climate. Total energy effects were calculated by summing the individual trees effects for the energy use for cooling and building characteristics. Effects were adjusted for building, climate effects, and electrical cooling emission factors (McPherson and Simpson, 1999). Finally total plot effects were aggregated to estimate total energy and associated effects on carbon emissions due to trees.

2.4. *Mitigating CO_2 emissions using urban forests*

We used plot level CO_2 sequestration estimates, USCB (2009) block data, and geostatistics to spatially analyze urban tree CO_2 offsets across both study areas. Based on spatial location of plots, semivariograms were used to analyze variability among plots and patterns of CO_2 sequestration. Ordinary kriging, a generalized least-squares interpolation method where the local mean is unknown and constant over the study area and a spherical semivariogram model with a variable searching radius of up to 10 plots was implemented to spatially display CO_2 sequestration (Goovaerts, 1997). The SGEMS application was used to analyze semivariograms and estimate kriging parameters (Remy, 2004) and ArcGIS desktop 9.3 (ESRI, 1999) was used to calculate the kriging surface and graphical output.

We also explored the effect of converting available planting spaces to urban trees for subsequent CO_2 sequestration by using idealized land use-specific net carbon sequestration densities (kg/ha/yr) and different levels of available planting space (ha). The available space for additional trees (ASAT) were considered the percent surface area in the measured plot (e.g. m^2 converted to ha) that was not currently occupied by trees, perennial vegetation, buildings, impervious or other recreational areas and where grown tree canopies will not present conflicts with existing infrastructure. Averages per land use type allowed us to estimate ASAT for the following land uses: residential, parks, vacant, and transportation which represent the most viable space available and are less likely to create conflict with other activities. The additional net carbon sequestration (ANC) due to the conversion of ASAT to trees was calculated using the formula:

$$ANC = \sum_{i=1}^{4} NCD_i \cdot ASAT_i \cdot p \tag{3}$$

where i = land use type identification with 1 = residential, park, 2 = vacant, 3 = park, and 4 = transportation, NCD_i = net carbon sequestration density (kg/ha/yr) associated with the *i*th land use type, $ASAT_i$ = amount of available space for additional trees (ha) associated with the *i*th land use type, and p = percentage of the total $ASAT_i$ to be used to enhance CO_2 sequestration (e.g. 25, 50 or 75 percent). Three scenarios of ANC were calculated and the projected amount of CO_2 sequestered by each of the three scenarios of ANC (PCR) was estimated as:

$$PCR = CCR + ANC \cdot f \tag{4}$$

where CCR = current CO_2 reduced (as estimated in this study), and f = molecular weight conversion factor of 3.7 units of carbon sequestered per units of CO_2 reduced. The conversion from ASAT to trees within a given land use assumes that these additional areas will "ideally" sequester carbon at a rate equivalent to that calculated for specific land uses in this study.

3. Results and discussions

3.1. *Urban forest structure*

There were approximately 37 million trees in Miami-Dade and 4.5 million in Gainesville (Table 3). Parks, vacant and forest land uses had greater tree densities in both cities. While 64 percent of the tree population in Miami-Dade is smaller than 7.6 cm in DBH, trees in Gainesville are more equally distributed among the different size classes (Table 3). Using methods similar to this study's, Zhao et al. (2010) report a 14 percent tree-palm canopy cover across Miami-Dade in 2008 and Escobedo et al. (2009b) report a 51 percent tree canopy cover in 2006 for Gainesville.

3.2. *Carbon storage and sequestration*

Even though trees with DBHs >30.6 cm accounted for only 5 percent and 16 percent of the tree population in Miami-Dade and Gainesville, respectively, they comprised 72 percent and 75 percent of the total C storage (Table 4). Larger per tree net C sequestration observed in Miami-Dade can be attributed to higher growth rates and/or lower carbon emitted due to tree condition (Table 3).

Table 3 – Tree attributes per land use categories in Miami-Dade County and Gainesville, FL.

	Land uses	Num. of trees	Percent of trees	#Trees/ha	Percent of trees per DBH class				
					2.5–7.6	7.7–15.2	15.3–30.5	30.6–61	>61
Miami-Dade	Agricultural	1,255,644	3.4	57	29.9	29.8	19.6	18.7	2.1
	Commercial	489,811	1.3	87	25	39.3	17.8	17.9	0
	Institution	2,245,610	6.1	405	37.1	41.8	18.3	2.8	0
	Park	11,147,061	30.4	983	83.9	9	3.9	2.2	1
	Residential	3,759,743	10.3	93	40	22.3	20.3	14.5	3
	Transportation	978,268	2.7	38	23.5	23.5	41.2	11.8	0
	Utility	252,662	0.7	41	0	40	60	0	0
	Vacant	16,347,497	44.5	597	66.3	28.8	3.3	1.4	0.2
	Wetland/Water	221,276	0.6	21	60	0	40	0	0
	Total[a]	36,697,571	100	227	63.7	22.8	8.5	4.2	0.7
Gainesville	Institution	261,767	5.8	364	30.1	23.3	19.4	27.2	0
	Park	128,975	2.8	476	44.2	16.9	22.1	15.6	1.3
	Residential	771,505	17	271	37.7	19.1	25.6	15.5	2.1
	Transportation	191,100	4.2	151	25.5	29.6	19.4	23.5	2
	Utility	392,267	8.6	132	93.8	0	6.3	0	0
	Vacant	91,190	2	272	25	34.1	20.4	18.1	2.3
	Forest	2,585,150	56.8	767	34.4	27.8	22.7	14.5	0.6
	Industrial	15,000	0.3	82	60	20	0	20	0
	Wetland/Water	110,940	2.4	531	51.2	18.6	16.3	14	0
	Total[b]	4,547,894	100	374	40	23.2	21.1	14.7	0.8

DBH, Diameter at Breast Height.
[a] Forest and industrial landuses were not present or had no trees in Miami-Dade.
[b] Agricultural and commercial landuses were not present or had no trees in Gainesville.

The residential land uses stored and sequestered the most C in Miami-Dade and Gainesville (Table 5). Land uses storing and sequestering substantial amounts of carbon include Parks and Vacant areas in Miami-Dade and Forests in Gainesville.

Net carbon sequestration per hectare in Miami-Dade is greater in Parks and Vacant areas and is due to greater tree densities, sizes, and growth rates. Similarly, Forests and Vacant uses in Gainesville showed high per area net sequestration. Even though these land uses are characterized by greater net C sequestration, they only encompass 24 percent and 30 percent of the total area in Miami-Dade and Gainesville, respectively.

Pine-oak, remnant forests in Gainesville and mangrove, agricultural tree orchards (e.g. *Persea americana*), and highly invasive *Melaleuca quinquinervia* tree stands in Miami-Dade are sequestering most of the carbon (Table 6). Spatial analyses show that *M. quinquinervia* in the northwest, mangroves and residential areas in the southeast, and patches of avocado orchards and remnant hammocks and pine rocklands in the southwest of Miami-Dade County are the areas sequestering the most carbon. Highly forested residential and remnant forests in central and eastern Gainesville are sequestering the most CO_2 (Fig. 1).

3.3. Anthropogenic CO_2 emissions and reduction strategies

A total of 32 million equivalent tons of CO_2 were emitted in Miami-Dade County in 2005 (Hefty et al., 2007); 15 times more

Table 4 – Number of trees, carbon (C) storage, and carbon storage per tree by size class.

		DBH class (cm)					Totals
		2.5–7.6	7.7–15.2	15.3–30.5	30.6–61	>61	
Miami-Dade	Number of trees	23,376,410	8,383,710	3,119,490	1,531,290	286,670	36,697,570
	Percent (%)	63.7	22.9	8.5	4.2	0.8	100
	C Storage (ton)	56,140	122,183	239,542	603,218	476,593	1,497,676
	Percent (%)	3.8	8.2	16	40.3	31.8	100
	C Storage/tree (Kg)	2.4	14.6	76.8	393.9	1662.5	40.8
	CO_2 Storage/tree (Kg)	8.8	53.4	281.6	1444.4	6095.9	149.6
Gainesville	Number of trees	2,578,357	1,501,856	1,361,491	942,872	58,672	6,443,248
	Percent (%)	40	23.3	21.1	14.6	0.9	100
	C Storage (ton)	7568	28,635	131,756	376,790	117,899	662,648
	Percent (%)	1.1	4.3	19.9	56.9	17.8	100
	C Storage/tree (Kg)	2.9	19.1	96.8	399.6	2009.5	60.5
	CO_2 Storage/tree (Kg)	10.8	69.9	354.8	1465.3	7368.0	221.8

Seq, Sequestration; CO_2, Carbon dioxide.

Table 5 – Total carbon storage and net carbon sequestration per land use type for Miami-Dade and Gainesville, Florida.

Land uses		C storage			Net C sequestration		
		tons	% of tons	tons/ha	tons/yr	% of tons/yr	Kg/ha/yr
Gainesville	Agricultural	166,207	11.1	7.6	11,379	7.4	517
	Commercial	48,973	3.3	8.7	2874	1.9	507
	Institution	78,053	5.2	14.1	7084	4.6	1277
	Park	341,027	22.8	30.1	36,750	23.9	3241
	Residential	408,764	27.3	10.1	15,402	10	380
	Transportation	100,276	6.7	3.9	5968	3.9	233
	Utility	10,131	0.7	1.7	2203	1.4	359
	Vacant	328,010	21.9	11.9	58,802	38.2	2146
	Wetland/Water	16,237	1.1	1.5	1384	0.9	129
	C Total	1,497,679	100	9.3	153,812	100	879
	CO_2 total	5,491,488		34	564,490		3221
Miami-Dade	Institution	34,714	7.4	48.2	1150	7.7	1597
	Park	7995	1.7	29.5	241	1.6	887
	Residential	102,072	21.8	35.8	3567	24	1253
	Transportation	28,641	6.1	22.7	886	6	701
	Utility	6442	1.4	2.2	438	2.9	147
	Vacant	20,597	4.4	61.4	542	3.6	1617
	Wetland/Water	13,678	2.9	65.5	375	2.5	1793
	Industrial	1669	0.4	9.2	69	0.5	377
	Forest	251,920	53.9	74.7	7615	51.2	2259
	C Total	467,728	100	38.4	14,882	100	1222
	CO_2 total	1,715,005		140.8	54,566		4482

than the emissions in Gainesville (GRU, 2007; Kappelman, 2007). Self-reported CO_2 emission reduction policy strategies from both Miami-Dade and Gainesville governments indicate that annual emission reductions in Gainesville were greater than those implemented in Miami-Dade (Table 1).

Based on this analysis, urban forest carbon sequestration through growth, shading, and climate regulation offset 3.4 percent and 1.8 percent of the total CO_2 emissions in Gainesville and Miami-Dade County, respectively (Table 7). Energy effects of avoided carbon due to both shading and climate accounted for only 0.8 percent of the total reduction in Gainesville and 0.2 percent in Miami-Dade (Table 7). In absolute terms or percent of the total amount of CO_2 reduced, urban trees offset 14.3 percent and 18.5 percent of the CO_2 reduced in Miami-Dade and Gainesville, respectively (Table 7). Based on the upper and lower thresholds, urban forests were

Table 6 – Total net carbon sequestration for common urban forest species in Miami-Dade and Gainesville, Florida.

	Tree species	Total Net C seq (mt/yr)	Percent of total C seq.	Average DBH (cm)	Number of trees (1000s)
Gainesville	*Quercus laurifolia*	1613	16.2	17.3	454
	Pinus elliotti	1297	15.1	20.2	835
	Pinus taeda	662	8.5	27.6	412
	Pinus glabra	466	8.4	14.5	40
	Quercus nigra	715	6.7	12.5	519
	Quercus viginiana	1503	6.7	37.3	86
	Acer rubrum	388	4.5	13.0	273
	Prunus caroliniana	522	3.6	8.3	113
	Liquidambar styraciflua	291	3.2	22.9	121
	Nyssa sylvatica	230	3.2	15.2	100
Miami-Dade County	*Melaleuca quinqinervia*	52,087	33.9	2.7	15,298
	Quercus viginiana	10,246	6.7	9.7	932
	Rhizophora mangle	9302	6	2.0	4703
	Persea americana	8403	5.5	14.9	279
	Bursera simaruba	7144	4.6	6.6	731
	Ficus aurea	6876	4.5	17.6	163
	Bucida buceras	5895	3.8	13.5	342
	Avicennia germinans	4702	3.1	6.6	860
	Ficus benjamina	4782	3.1	2.8	1359
	Conocarpus erectus	4509	2.9	2.1	2090

C, Carbon; mt, Metric tons; seq, Sequestration; DBH, Diameter at breast height.

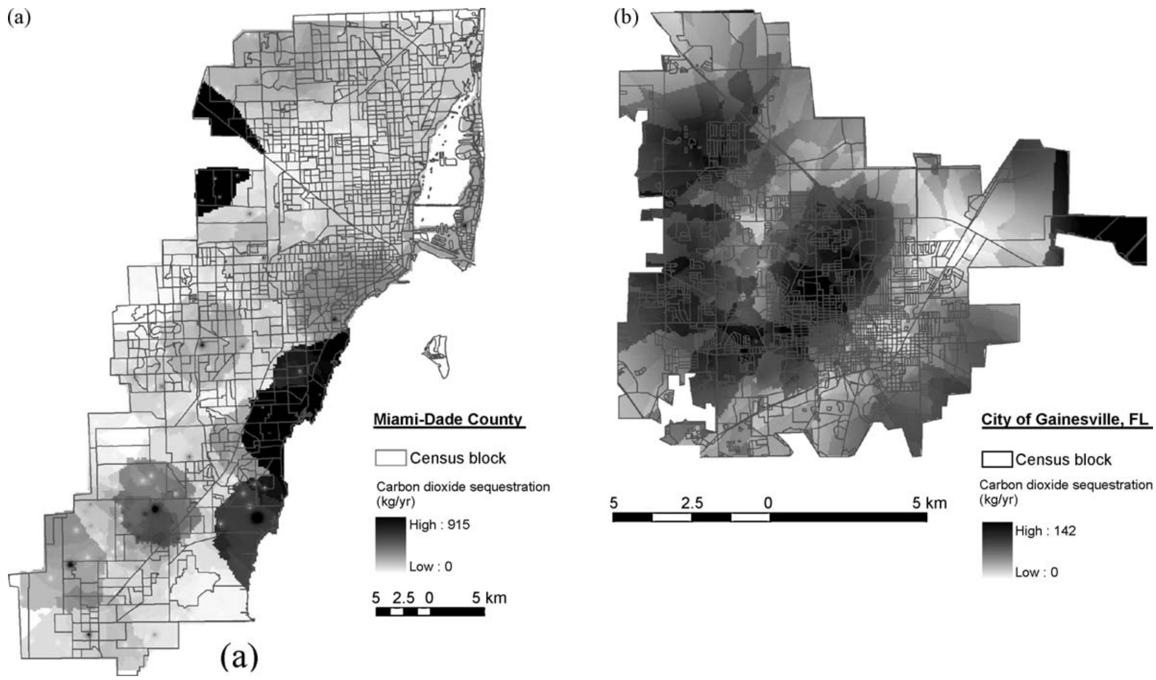

Fig. 1 – Spatial patterns of carbon dioxide sequestration in the urbanized portion of Miami-Dade County (a) and in the city limits of Gainesville, Florida (b). Note, greater carbon dioxide sequestration rates in Miami-Dade are due to dense stands of large sized, *Melaleuca quinquinervia*.

moderately effective at sequestering CO_2 relative to the other strategies in Miami-Dade and Gainesville.

3.4. *Enhancing CO_2 emission reduction through urban forests*

Opportunities to use urban tree plantings and conversion of available land into urban forests in Miami-Dade and Gainesville would depend on the amount of available space for additional trees and land use limitations. Public lands in the form of parks, right of ways (e.g. transportation and utility), vacant areas, and institutional areas probably present the most opportune areas for trees (Fig. 2). Among these publicly owned lands, utility areas usually are not able to sustain trees due to current land use designations such as recreation fields, airports, and other facilities (Fig. 2). In Miami-Dade, public land uses offering ASATs are vacant areas and transportation uses (102 km^2 in total). In Gainesville, publicly owned ASAT are mostly concentrated on transportation landuses (4.2 km^2).

The ASAT in the residential land use is more abundant than other private and public uses in both cities (Fig. 2). Enhancing tree coverage on these landuses should have a greater effect on CO_2 reduction due to tree-building interactions (McPherson, 1998). Conversion of 75 percent of the available space to urban forests would increase CO_2 offsets from 3.4 to 5.7 percent in Gainesville (Table 8). Since the amount of available space on these land uses are proportionally larger in Gainesville than in Miami-Dade, this difference cannot be

Table 7 – Carbon dioxide (CO_2) emission reduction from urban forest offsets in Gainesville and Miami-Dade, Florida, USA.

Approaches to reduce CO_2 emissions	Gainesville Total emission: 2,097,627 tons of CO_2			Miami-Dade Total emission: 31,967,000 tons of CO_2		
	Emission reduction (tons/ha/yr)	Relative reduction (per approach)	Absolute reduction (of total)	Emission reduction (tons/ha/yr)	Relative reduction (per approach)	Absolute reduction (of total)
Median (Lower threshold)[a]	2.2	1.1%	4.3%	2.6	0.7%	7.1%
Arithmetic mean (Upper threshold)[a]	11.7	5.1%	21.5%	5.2	2.0%	20.4%
Urban forests effects						
CO_2 sequestration	4.5	2.6%	11.0%	3.2	1.6%	16.7%
CO_2 avoided due to shade	0.65	0.38%	1.6%	0.166	0.084%	0.86%
CO_2 avoided due to climate regulation	0.70	0.41%	1.7%	0.173	0.087%	0.90%
Total urban forest offsets	5.9	3.4%	14.3%	3.5	1.8%	18.5%

[a] The criteria to assess efficacy is based on Table 1.

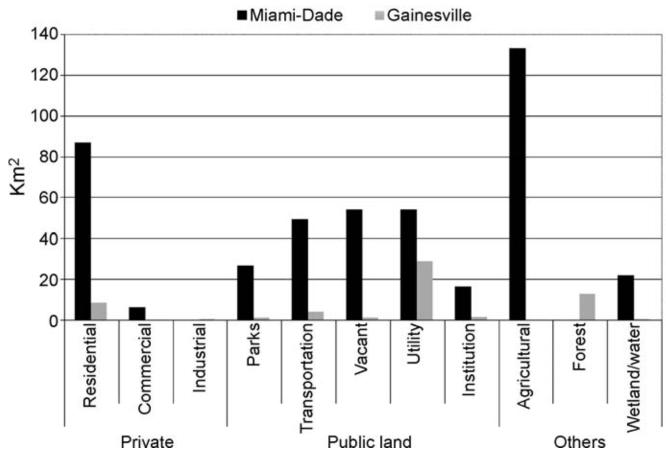

Fig. 2 – Available planting space (km^2) by land use in Miami-Dade and Gainesville, Florida.

attributed to more abundant ASAT in Miami-Dade but rather to greater net carbon sequestration rates due to Gainesville's tree density and species composition.

The conversion of ASATs has the potential to increase absolute reduction up to 37 percent and 24 percent in Miami-Dade and Gainesville, respectively. However, the conversion of available areas into more forested areas may bring some inconvenience to the community. Less shade on homes, better visibility, and better aesthetic compatibility with gardens were presented as frequent reasons for favoring less dense configurations (e.g. using 50 percent of available space) on private residencies and public rights of ways (Varela, 2008). The perceived risk of damage by trees during hurricanes, litter removal, and tree maintenance costs are additional constraints towards increasing tree cover in Florida (Escobedo et al., 2008).

3.5. *Management strategies for reducing anthropogenic emissions of CO_2*

Remnant forests, mangroves and residential areas characterized by larger trees sequestered more CO_2 than smaller, recently planted, trees in other urban land uses. Shallow soils and hurricane damage in Miami-Dade (Szantsoi et al., 2008) appears to be limiting urban tree growth and sequestration rates. Urban forest structure and urbanization patters determined CO_2 sequestration patterns in both cities. Carbon uptake will decrease as the forest matures and urbanization increases. So, managing for natural regeneration and tree plantings are necessary to compensate for the C emitted from previously removed vegetation in forested areas. This is especially important in parks, residential, and vacant areas in Gainesville and Miami-Dade, where the average tree DBH is larger than other land uses. By regenerating new trees, increasing amounts of CO_2 can be stored until equilibrium is reached, thus offsetting decomposition from dead trees (Jo, 2002; McPherson, 1998).

Our results indicate that urban forest management was moderately effective at offsetting annual CO_2 emissions relative to other reduction strategies but total CO_2 offsets, particularly planting small trees in urbanized land uses, were minimal. Therefore preserving large trees and protecting existing forests during urbanization might be more effective at offsetting CO_2 than massive tree plantings. Increasing the amount of layers using shrubs and smaller trees is also an important way to improve carbon sequestration and provide secondary ecosystem services such as mitigation of wind storm damage (Duryea et al., 2007; Escobedo et al., 2009a). In the case on Miami-Dade County, over 30 percent of the actual net C sequestration is in stands of *M. quinquinervia*, an undesirable, highly invasive, exotic tree. Thus, current invasive tree eradication programs could result indirectly in decreasing carbon sequestration, tree cover, and related ecosystem services in areas of Miami-Dade.

Table 8 – Current and projected emission reductions due to urban forests using three levels of available space enhanced with urban trees within residential, parks, vacant and transportation land use types.

	Available space used (%)	Miami-Dade			Gainesville		
		Emission reduction (tons/ha/yr)	Relative reduction (%)	Absolute reduction (%)	Emission reduction (tons/ha/yr)	Relative reduction (%)	Absolute reduction (%)
Current	0	3.6	1.8	18.5	5.8	3.4	14.3
Projected	25	4.8	2.4	24.7	7.2	4.2	17.5
	50	5.9	3.0	30.9	8.5	4.9	20.8
	75	7.1	3.6	37.1	9.8	5.7	24.0

4. Conclusions

Management alternatives need to consider well defined and long-term community objectives and perceptions towards trees and preservation of existing urban forest structure when planning and sustainably managing for climate change mitigation. Strategies to reduce emitted carbon by urban forests should also be weighed against the variety of ecosystem services provided by trees as they interact with the urban environment and changing economic trends. Tree selection and management objectives need to consider the multiple- and often conflicting—ecosystem services they provide (e.g. CO_2 sequestration and increased tree shading versus allergencitiy, tree debris, and maintenance needs). Furthermore, the use of low-maintenance, fast growing, non-native trees should consider their potential invasive traits and negative ecological effects to remnant, peri-urban natural ecosystems. Although CO_2 offsetting is timely, mitigation of hurricane damage, preservation of wildlife habitat, stormwater reduction, and beautification of communities are just a few examples of other ecosystem services that might be just as relevant to decision makers and the community.

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REFERENCES

(ACEPD) Alachua County Environmental Protection Department, 2001. Greenhouse Gas Inventory for Alachua County Governmental Operations and the Alachua County Community. Accessed Oct 1, 2009 at: http://alachuacounty.us/assets/uploads/images/epd/polution/GHG-Inventory2001.pdf.

Avijit, G., 2002. Geoindicators for tropical urbanization. Environmental Geology 42, 736–742.

Duryea, M.L., Kampf, E., Littell, R.C., Rodríguez-Pedraza, C.D., 2007. Hurricanes and the urban forest: II. Effects on tropical and subtropical tree species. Arboriculture and Urban Forestry 33 (2), 98–112.

(ESRI) Environmental Systems Research Institute, 1999–2008. ArcGIS: Release 9.3 [software]. Redlands, California: Environmental Systems Research Institute.

Escobedo, F., Seitz, J., Northrop, R., Moon, M., 2008. Community Leaders' Perceptions on Urban Forests in Hillsborough County, Florida. University of Florida- IFAS, EDIS FOR194. Accessed Oct 1, 2009 at: http://edis.ifas.ufl.edu/document_fr255.

Escobedo, F., Luley, C., Bond, J., Staudhammer, C., Bartel, C., 2009a. A hurricane debris and damage assessment for Florida urban forests. Arboriculture and Urban Forestry 35 (2), 100–106.

Escobedo, F., Seitz, J., Zipperer, W., 2009b. Gainesville's Urban Forest Canopy Cover. University of Florida- IFAS, EDIS FOR 215. Accessed March 3, 2010 at http://edis.ifas.ufl.edu/document_fr277.

(GRU) Gainesville Regional Utilities, 2007. Climate Protection Strategies. Presentation to the Gainesville City Commission, November 26, 2007. Accessed Oct 1, 2009 at: http://legistar.cityofgainesville.org/attachments/5938.pdf.

Goovaerts, P., 1997. Geostatistics for Natural Resources Evaluation. Oxford University Press, USA, 496 pp.

Hefty, N., Gandi, V., Griner, D., Baker, R., Wong, H.P., 2007, Miami-Dade County's Global Climate Change - Urban CO_2 Reduction Plan. Accessed Oct 1, 2009 at: http://www.miamidade.gov/derm/library/air_quality/CO2_Reduction_Final_Report.pdf.

Jim, C.Y., Liu, H.T., 2001. Species diversity of three major urban forest types in Guangzhou City, China. Forest Ecology and Management 146, 99–114.

Jo, H.K., McPherson, E.G., 1995. Carbon storage and flux in urban residential greenspace. Journal of Environmental Management 45, 109–133.

Jo, H.K., 2002. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. Journal of Environmental Management 64, 115–126.

Karl, T.R., Nicholls, N., Gregory, J., 1997. The coming climate. Scientific American 5, 78–83.

Kappelman, R.L., 2007. City of Gainesville: Baseline year 1605(b) Green House Gas (GHG) Inventory Report. Accessed Oct 1, 2009 at: https://govconnect.alachuacounty.us/committees/ECSC/Strategies/Shared%20Documents/GRU%20%20Interim%201605%20b%20GHG%20report%20rev%2041.pdf.

McPherson, E.G., 1998. Atmospheric carbon dioxide reduction by Sacramento's urban forest. Journal of Arboriculture 24, 213–215.

McPherson, E.G., Simpson, J.R., 1999. Carbon Dioxide Reductions Through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters. Gen. Tech. Rep. PSW GTR-171, USDA Forest Service, Pacific Southwest Research Station, 237 pp.

Nowak, D.J., Crane, D.E., Stevens, J.C., Ibarra, M., 2002. Brooklyn's Urban Forest. Gen. Tech. Rep. NE-290, US Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA.

Nowak, D.J., Crane, D.E., 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution 116, 381–389.

Pearson, P.N., Palmer, M.R., 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. Nature 406, 695–699.

Remy, N., 2004. The Stanford geostatistical earth modeling software (SGeMS): a tool for new algorithm development. In: Leuangthong, O., Deutsch, C.V. (Eds.), Geostatistics Banff 2004. Springer, Dordrecht, pp. 865–872.

Spector, T., Putz, F.E., 2006. Crown retreat of open-grown southern live oak (*Quercus viginiana*) due to canopy encroachment in Florida, USA. Forest Ecology and Management 228, 168–176.

Szantsoi, Z., Escobedo, F., Dobbs, C., Smith, S., 2008. Rapid methods for estimating and monitoring tree cover change in Florida urban forests: the role of hurricanes and urbanization. In: Bettinger, P., Merry, K., Fei, S., Drake, J., Nibbelink, N., Hepinstall, J. (Eds.), Proceedings of the 6th Southern Forestry and Natural Resources GIS Conference. pp. 93–104.

(UN) United Nations, 2006. World Urbanization Prospects: The 2005 Revision. Population Division, Department of Economic and Social Affairs, United Nations, New York.
(USCB) United States Census Bureau, 2009. U.S. Census Bureau: Density Using Land Area, For States, Counties, Metropolitan Areas, And Places. Accessed March 3, 2010 at http://www.census.gov/population/www/censusdata/density.html.
Varela, S.I., 2008. Urban biological corridors and their socio-environmental implications. A plan to establish a green infrastructure in Northwest Philadelphia, PA. MS Thesis. State University of New York-College of Environmental Science and Forestry, Syracuse.
Winsberg, M.D., 2003. Florida Weather, 2nd ed. University Press of Florida, Gainesville, FL, 240 pp.
Zhao, M., Escobedo, F., Staudhammer, C., 2010. Spatial patterns of a subtropical, coastal urban forest: implications for land tenure, hurricanes, and invasives. Urban Forestry and Urban Greening. In Press, ISSN 1618-8667, doi:10.1016/j.ufug.2010.01.008.

Francisco Escobedo is an assistant professor at the University of Florida's School of Forest Resources and Conservation. His research focuses on urban forest management and planning, the ecosystem services of urban and urbanizing forests, and the effects of urbanization and other disturbances on forests and human settlements. He holds a PhD in Natural Resources and Environmental Policy.

Sebastian Varela is research assistant at the University of Florida's School of Forest Resources and Conservation. His MS is in urban and landscape ecology from the State University of New York. He has a BS in Forest Engineering from the University of Chile.

Min Zhao is an associate professor at the Urban Ecology and Environment Research Center in Shanghai Normal University, China. Her research focuses on quantifying urban forest function and carbon dynamics in urban forests in China and the US. She is a Doctor of Science from the Institute of Botany, Chinese Academy of Sciences.

John E. Wagner is an associate professor of forest resource economics at the State University of New York-ESF. His research focuses primarily on developing mathematical and economic models to critically analyze questions concerning the sustainable management and use of forest resources. He has a PhD from Colorado State University.

Wayne Zipperer joined the USDA Forest Service in 1987 as a research forester. He conducts research on the affects of urbanization on ecosystem patterns and processes. He has a PhD from SUNY- Environmental Science and Forestry.