Landscape and Urban Planning 131 (2014) 64–73

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

The influence of subdivision design and conservation of open space on carbon storage and sequestration

Richard M. Vaughn[a,*], Mark Hostetler[b], Francisco J. Escobedo[c], Pierce Jones[d,e]

[a] School of Natural Resources & Environment, University of Florida, United States
[b] Wildlife Ecology & Conservation, University of Florida, United States
[c] School of Forest Resources & Conservation, University of Florida, United States
[d] Agricultural and Biological Engineering, University of Florida, United States
[e] Program for Resource Efficient Communities, University of Florida, United States

HIGHLIGHTS

- Used design scenarios to asses impacts on carbon storage and sequestration.
- Old tree stands provided the greatest savings of carbon storage and sequestration.
- Over 91% of existing carbon storage and 82% of sequestration could be maintained.

ARTICLE INFO

Article history:
Received 26 June 2013
Received in revised form 17 July 2014
Accepted 3 August 2014
Available online 28 August 2014

Keywords:
Carbon storage
Carbon sequestration
Compact design
Forest type
Open space
Tree stand age

ABSTRACT

Cities are increasingly trying to offset carbon dioxide emissions and existing and new residential developments, or urban subdivisions, are a major source of such emissions. Compact or clustered subdivision designs have the potential to improve carbon storage and sequestration through the conservation of open space and the preservation of existing trees found on built lots. However, very few empirical studies assess how different subdivision designs and tree preservation strategies affect the carbon footprint of proposed residential developments. Using a 705 ha pine plantation that has been approved for the development of 1835 residential units near Gainesville, Florida, our objectives were to determine which site designs and tree preservation strategies could maximize carbon sequestration and storage. From 80 stratified random plots, we measured and analyzed tree and plot characteristics according to forest type and tree stand age categories. Tree data collected from these plots were analyzed with the i-Tree ECO model to estimate baseline predevelopment carbon stores and sequestration rates. Using ArcMap, we then assessed the impact, on baseline carbon sequestration and storage capacity, of several different site designs and tree conservation scenarios for the proposed development. Up to 91% of carbon storage and up to 82% of carbon sequestration could be maintained through a cluster urban development design and by preserving older tree stands. Results indicate that a subdivision's carbon footprint can significantly improve when forest types and tree preservation are incorporated into the design of a development.

1. Introduction

As climate change continues to become a serious environmental and societal concern, many urban areas will come under increased pressure to balance continued population growth with greenhouse gas (GHG) reduction. Climate change is a direct result of GHG emissions and a variety of human activities consume fossil fuels and release GHGs into the atmosphere (Malhi, Meir, & Brown, 2002; Soloman et al., 2007). Of these, carbon dioxide (CO_2) is of great concern, making up approximately half of all emissions (Soloman et al., 2007). Since forests store and sequester carbon, conservation and restoration could help offset carbon emissions worldwide (Brown, Swingland, Hanbury-Tenison, Prance, & Myers, 2002). However, globally, forested areas have been in decline for decades and 13 million hectares were lost every year since 2000 (Food & Agriculture Organization of the United Nations, 2010). Causes for deforestation vary based on a region's specific needs

---

* Corresponding author. Present address: Department of Wildlife Ecology & Conservation, University of Florida, 110 Newins-Ziegler Hall, PO Box 110430, Gainesville, FL 32611-0430, United States. Tel.: +1 502 905 0619.

E-mail addresses: ecokaidiver@hotmail.com (R.M. Vaughn), hostetm@ufl.edu (M. Hostetler), fescobed@ufl.edu (F.J. Escobedo), piercejones@ufl.edu (P. Jones).

http://dx.doi.org/10.1016/j.landurbplan.2014.08.001
0169-2046/

and can be mostly attributed to land use changes such as agricultural development, urban expansion, and wood extraction (Geist & Lambin, 2002).

New residential subdivisions are usually sited on rural greenfield sites along the edge of existing established urban areas. This peri-urban region typically represents a large source of carbon emissions as forests have been replaced with houses and roads (Zhang et al., 2008). Development typically follows a pattern of clearing a site of all flora, recontouring the site, and then planting trees of similar size and species throughout the entire construction area. When new developments remove existing trees for construction and then plant new trees, carbon stores are released from the destruction of the mature trees and this is followed by a lengthy lag in carbon sequestration as the new trees mature (Escobedo, Varela, Zhao, Wagner, & Zipperer, 2010; Nowak & Crane, 2002). When tree cover is replaced with impervious surfaces or even open park spaces that require mowing, irrigation, and fertilization, areas that were previously carbon sinks can shift to carbon emission sources (Dobbs, Escobedo, & Zipperer, 2011).

When land is subdivided, conserving forests and large individual trees can help minimize a development's carbon footprint by maximizing carbon storage and sequestration (Escobedo et al., 2010; Jo, 2002; Nowak & Crane, 2002). Urban forests can reduce CO_2 emissions through photosynthesis and storage in biomass, and can sequester more carbon than natural forests on a per unit tree basis due to the open forest structure (McPherson, Nowak, & Rowntree, 1994). In addition, trees can shade homes and decrease ambient air temperature through evapotranspiration further limiting CO_2 emissions by reducing energy needs for heating and cooling homes (Jo & McPherson, 2001; Nowak & Crane, 2002). Not only could the overall design of development maximize carbon sequestration and storage, but it could promote a number of other natural resource goals such as conserving wildlife habitat, water quality, and biodiversity (Arendt, 1996; Hostetler, 2012; Milder, 2007).

Conservation developments, areas where homes are clustered together on smaller lots conserving as much greenspace as possible, are alternative subdivision designs that integrate human needs with natural resource conservation (Arendt, 1996; Hostetler & Drake, 2009; Milder, 2007). Conservation developments can reduce the overall carbon footprint of the planned subdivision if the placement of built lots maximizes carbon storage and sequestration for the site. For example, subtropical wetland forests sequester more carbon than upland pine forests (Escobedo et al., 2010), and placing homes in pine forests instead of wetland forests would increase carbon storage and sequestration for developments in subtropical areas. Analyzing the potential impacts of different subdivision designs on carbon sequestration and storage could provide city planners and developers with information on the levels of carbon benefits of one design versus another, which may ultimately improve the overall carbon footprint of a city.

Previous studies of urban tree carbon sequestration and storage have focused on city and land use level estimates in existing urban areas (Escobedo et al., 2010; Jo & McPherson, 2001; Maco & McPherson, 2003; Nowak & Crane, 2002). Little research, however, has explored how different subdivision designs impact carbon sequestration and storage before a development has been constructed. In this study, we selected a forested peri-urban area near Gainesville, Florida that is currently managed for timber. Development approval has been obtained for this site which will eventually contain a mixture of residential and commercial land uses. Our objectives were to (1) determine the influence of different forest types and tree stand ages on carbon storage and sequestration within the site and (2) assess how different subdivision designs impact carbon storage and sequestration. The results of this study will provide some of the information that developers, planners, and designers need to help increase carbon storage and sequestration, and reveal how the structure of managed forests can be used to offset the carbon emissions of households.

Table 1
Seventeen land use land cover (LULC) classifications were grouped into three forest types on the Gainesville 121 site.

Forest type	Land use land cover
Hydric	Bay/Gum/Cypress ecological complex
	Loblolly bay forest
	Swamp forest ecological complex
	Cypress forest compositional group
	Temperate wet prairie
	Forb emergent marsh
	Water lily or floating leaved vegetation
	Saturated-flooded cold-deciduous and mixed evergreen/cold-deciduous shrubland ecological complex
Mesic-Hydric	Mesic–hydric live oak/sabal palm ecological complex
	Mesic–hydric pine forest compositional group
	Broad-leaved evergreen and mixed evergreen/cold-deciduous shrubland compositional group
Xeric–mesic	Xeric–mesic mixed pine/oak forest ecological complex
	Live oak woodland
	Mixed evergreen, cold-deciduous hardwood forest
	Sandhill ecological complex
	Dry prairie (xeric–mesic) ecological complex
	Gallberry/saw palmetto shrubland compositional group

2. Methods

2.1. Study area

The location of this study area is north of Gainesville, Florida on State Route 121 (29° 43′ N, 82° 21′ W). Gainesville is located in North Central Florida, USA and has a population of 125,326 (United States Census Bureau, 2011). Gainesville's climate is humid and subtropical with an average temperature of 12.5 °C in January and 26.2 °C in June. The January mean monthly rainfall is 83.8 mm and in June is 173.0 mm (National Oceanic & Atmospheric Administration, 2011). Over half (56.2%) of soils are a combination of Pomona, Wauchula, and Monteocha loamy sand (Natural Resources Conservation Service, n.d.). This study area, hereafter called the Gainesville 121 site, was chosen because it is in the initial stage of urban development and land owners are interested in determining how carbon storage and sequestration could be improved using different development designs. The development site is currently owned by Plum Creek and is comprised of 705 ha of planted pine, mixed hardwood forest, and wetlands. At the time field work was conducted, the site was approved for 1835 residential units.

2.2. Land cover aggregation

Analysis of land cover raster data generated by the Florida Fish and Wildlife Conservation Commission (Florida Fish & Wildlife Conservation Commission, 2003) using ArcMap software revealed that the study area is comprised of 21 Land Use and Land Cover (LULC) types. Four of these LULC classifications, bare soil/clear-cut, urban residential, agriculture, and pasture/grassland/agriculture, (a total of 18 ha), were excluded because one of the goals of this study was to determine pre-construction tree carbon storage and sequestration in the study area. To better represent the major plant community types in the study area, the remaining seventeen LULC types were aggregated into three forest type classes (hydric, mesic–hydric, and xeric–mesic) based on soil moisture regimes and species composition (Table 1). Forest type classification was determined by comparing metadata descriptions of soil moisture profiles and vegetative species with the LULC classification scheme in Florida Fish and Wildlife's final report (Kawula, 2009) and

Fig. 1. Three forest types (mesic–hydric, hydric, and xeric–hydric) found on the Gainesville 121 development site in Florida.

descriptions from the Florida Geographic Data Library for Florida Land Cover (Florida Fish & Wildlife Conservation Commission, 2003), and regional plant classifications (Godfrey, 1988). These three forest type classifications also represent the different biomass ranges in soils on the site (Slik et al., 2010). Hydric sites are usually nutrient rich, allowing trees to have a higher biomass than in nutrient poor areas, such as some upland or scrub sites, where competition for resources could result in lower biomass accumulation. Furthermore, certain species of trees are typically found in certain soil types (e.g., cypress trees tend to be in hydric areas). Thus, this classification can be used to determine if carbon storage and sequestration is different between classes.

ArcMap was then used to transform the 7777 thirty-meter LULC raster cells (931 xeric–mesic, 5393 mesic–hydric, and 1453 hydric) into three large polygons representing each new forest type class (Fig. 1). These polygons were used to generate stratified, random plot center points, which resulted in 11 hydric, 54 mesic–hydric, and 15 xeric–mesic plot sites. Sample sizes were proportional to the area of each polygon.

2.3. Field sampling

From June through October 2011, 0.04 ha plots were established and tree measurements taken for each of the 80 sample plots. Plot center-points in the field were located using a hand-held Garmin GPSmap 76S unit. Each plot center-point was flagged and given a unique identification number. Tree data collection methodology was based on Nowak et al. (2008). All trees, living or dead with a diameter at breast height (DBH) > 2.5 cm and with greater than one-half of the bole in the plot were counted. Tree characteristics measured during data collection were species, number of stems, DBH, total height, crown height, crown width, percent canopy cover missing, dieback, and crown light exposure. Due to very high tree densities within sample plots, tree species characteristics were based on calculated averages from the first three random trees measured from each species type within a sample plot. The only characteristic measured for every tree within the sample plot was diameter at breast height since it plays such an important role in estimating carbon storage and sequestration in forest communities.

Table 2
Estimated tree attributes and species per forest type category based on field measurements of 80, 0.04 ha plots on the Gainesville 121 site.

Forest type	Hectares	Number of trees	Trees/ha	Number of species	Top 3 Species	Top 3 as % of total trees
Hydric	134	167,500	1250	18	PIEL, QUNI, QUHE	26.7
Mesic–hydric	486	680,400	1400	16	PIEL, QUHE, ACBA	72.4
Xeric–hydric	85	140,250	1650	9	PIEL, QUNI, PITA	72.5

ACBA, *Acer barbatum*; QUHE, *Quercus hemisphaerica*; QUNI, *Quercus nigra*; PIEL, *Pinus elliottii*; PITA, *Pinus taeda*.

DBH was recorded for all trees and averaged for each species within each plot. Measurements were only taken within 0.01 ha subplots (i.e. the northeast quarter of the 0.04 ha plot) in order to reduce sampling effort following (Zhao, Escobedo, & Staudhammer, 2010) procedure. During subsequent analyses, individual trees on these one-quarter subplots were multiplied by a factor of four before analyzing in i-Tree. Field information was uploaded into the i-Tree Eco model (Nowak et al., 2008) to calculate total tree carbon sequestration and storage for the entire study area.

The i-Tree ECO software is adapted from the UFORE model and is an urban forest management application designed to analyze field data collected from complete inventories or from randomly located plots (http://www.itreetools.org/eco/). Carbon storage and sequestration calculations are based on a series of species-specific, genus or family biomass allometric equations from several literature resources (Nowak et al., 2008).

2.4. Scenario and analyses development

In addition to exploring forest types, we also calculated average carbon storage and sequestration for different tree stand age groups throughout the study area from data supplied by the landowner. Previous research has shown a moderate correlation, ($R^2 = 0.4–0.6$) between tree age and DBH (Loewenstein, Johnson, & Garrett, 2000). But, stand age is an important factor in carbon storage and sequestration because older subtropical forest stands generally contain larger trees which store and sequester more carbon (Timilsina et al., 2013). Therefore, in this managed site, it might be better to target older tree stands for preservation than to target specific forest type classes. Tree stand spatial data, were merged in ArcMap with sample plot data in order to determine the number of study plots found in each tree stand age group. Tree stand age groups were 2–9, 10–18, 19–29, and 30–61 yrs. Differences in age group categories were generated randomly using ArcGIS. These groupings were kept since they closely resemble timber harvesting cycles, which usually occur once in a 10–15 yr period. Average carbon sequestration and storage values were calculated for each tree stand age group. We used Student's *t*-tests to determine whether sequestration and storage differed significantly between forest types and tree stand age groups ($\alpha = 0.05$).

We explored eight different building design and layout scenarios to explore compact and fragmented designs more fully in ArcMap using the assumption that all buildable areas would be cleared of all vegetation. The first was the original permitted design with a mix of residential, commercial, and conservation areas, the others allocated building footprints in different parts of the study area to better explore compact and more fragmented designs. Based on the above analyses, we used either forest types or tree stand age strata to target forested areas for conservation. For example, if carbon storage and sequestration were significantly different between certain tree stand age groups (and not so for the three forest type groups), then tree stand age strata were targeted for conservation instead of forest type. After a scenario goal had been determined, forested areas were selected for conservation according to the scenario's overall goal. The resulting carbon storage and sequestration for each of the eight subdivision development scenarios were compared against the benchmark estimates. Details for each scenario goal are given in Section 3 below.

3. Results

3.1. Forest type, tree stand age, and benchmark carbon

A total of 26 different tree species were identified in the sample plots. The three most frequent species were Slash Pine (*Pinus elliottii*) at 48.4%, Darlington/Laurel Oak (*Quercus hemisphaerica*) at 9.8%, and Water Oak (*Quercus nigra*) at 8.5% comprised approximately 66.8% of all species found in the sampled plots (Table 2). From data provided by the landowner, 68% of the entire site was categorized as managed pine plantation and the other 32% was categorized as hardwood forest. Analyses of carbon sequestration of forest types indicted no differences (all $P > 0.05$). For carbon storage, only hydric forest stored significantly more carbon then mesic–hydric ($P = 0.0002$). All other comparisons of carbon storage among forest types were not significant (all $P > 0.05$: Table 3). For tree stand age categories 19–29 and 30–61 yrs, 6 plots were in hydric forest, 16 plots were in mesic–hydric, and 8 plots were in xeric–mesic. Notably, 55% of all hydric plots were located in the 30–61 yrs (the oldest category), while only 7% of mesic–hydric plots were in the same category. Of all trees measured in sample plots, *Pinus* spp. accounted for 24% of trees in the hydric class, 58% of trees in mesic–hydric, and 55% of trees in xeric–mesic. In the hydric area, large, older trees, mostly oak (*Quercus* spp.), cypress (*Taxodium* spp.), and sweetgum (*Liquidambar styraciflua*) were storing most of the carbon (66%), while pine was storing the greatest share of carbon in mesic–hydric (60%) and in xeric–mesic (91%).

With tree stand age analyses, the two older tree stand age categories (19–29 and 30–61 yrs) had significantly higher amounts of carbon storage and sequestration than the younger tree stands of 2–9 and 10–18 yrs ($P < 0.05$; Table 4). The one exception was carbon

Table 3
Carbon storage and annual sequestration for the Gainesville 121 site by percentage and average metric tons (t) per hectare (ha) for each forest type.

Forest type	Hectares	Carbon storage			Gross carbon sequestration		
		(t)	% (t)	(t/ha)[a]	(t/yr)	% (t/yr)	(t/ha/yr)[a]
Hydric	134	10,946	37.37	81.7[b]	577	20.79	4.3
Mesic–hydric	486	14,933	50.99	30.9	1807	65.09	3.7
Xeric–mesic	85	3349	11.43	39.4	392	14.12	4.6
Total	705	29,288	100		2776	100	

[a] Hydric: $n = 11$, Mesic–hydric: $n = 54$, Xeric–mesic: $n = 15$.

[b] $P < 0.05$ for hydric versus mesic–hydric.

Table 4
The average amount of carbon storage (metric tons per hectare) and yearly sequestration (metric tons per hectare per year) for each tree age group found at the Gainesville 121 site. Averages are based on plot level data generated from 80, 0.04 ha plots.

Tree age group (yrs)[a]	Plots (*n*)	Avg. C storage-(t/ha)	S.E.	Avg. gross C seq.-(t/ha/yr)	S.E.
Age 2–9	24	9.2	2.0	2.1	0.4
Age 10–18	26	29.0	4.6	3.9	0.5
Age 19–29	19	44.8	4.3	4.5	0.3
Age 30–61	11	120.9	22.4	7.0	1.0

[a] $P < 0.05$ for all comparisons between older age groups (19–29 yrs, 30–61 yrs) and younger age groups (2–9 yrs, 10–18 yrs); except age 10–18 yrs versus 19–29 yrs sequestration.

sequestration when comparing 10–18 to 19–29 yrs tree stand age categories ($P > 0.05$).

3.2. Development scenarios and carbon storage and sequestration

Given the above results, we used tree stand age, instead of forest type, to explore the effect of different designs on tree carbon storage and sequestration. For each of the eight development scenarios, land was allocated for construction, and changes in carbon were calculated by multiplying the average carbon storage and sequestration by the area (ha) of each tree stand age group remaining after allocation. Scenario 1, the existing permitted design that delineated different land uses, represents the benchmark. The comparisons with the benchmark original design are discussed in detail in the next section.

3.3. Benchmark

The results are based on allometric equations and are a snapshot in time because trees are constantly in a state of ecological succession. At the end of data collection, the Gainesville 121 site (predevelopment) was storing approximately 29,938 metric tons (t) and annually sequestering 2857 t of carbon (Table 5).

3.4. Scenario 1: permitted construction

The current permitted construction design calls for 1835 units on 415 buildable hectares (Fig. 2A). The buildable space is comprised of 84% residential housing and 16% commercial space. According to the Comprehensive Plan Future Land Use Element, residential densities for the permitted design scenario call for a maximum single family unit rate of 1 residential unit per 1.0 ha and a low-density residential maximum unit rate of 2.75 units per 0.4 ha, plus a mixed use, planned use district (commercial) that requires a minimum density of 4 units per 0.4 ha (Radson, 2010). The remaining 290 ha of the study site were designated as conservation areas by a City of Gainesville approved Development Order (Radson, 2010). Most of the conservation area (approximately 90%) is comprised of wetlands. Results of the impact to benchmark carbon values indicate that 16,338 t (55%) of carbon storage and 1327 t (46%) of annual carbon sequestration will be conserved with this design (Table 5).

3.5. Scenario 2: doubled residential density and halved buildable area

To meet the goal of scenario 2 of decreasing buildable space to conserve more trees, the area of each tree stand age group that was cleared for building was reduced by 50%. Therefore to achieve the same number of residential units, the unit density per ha was doubled (Fig. 2B). Instead of 415 buildable ha, the site now has 207 ha while residential units are held constant at 1835 RUs. Based on local conversations with county planners, this doubling of density was a realistic scenario and could be constructed under current policy. This resulted in conserving 77% of stored carbon and 73% of sequestered carbon (Table 5). All following development scenarios in this study used a 50% hectare and double density formula.

3.6. Scenario 3: conserving older tree stands

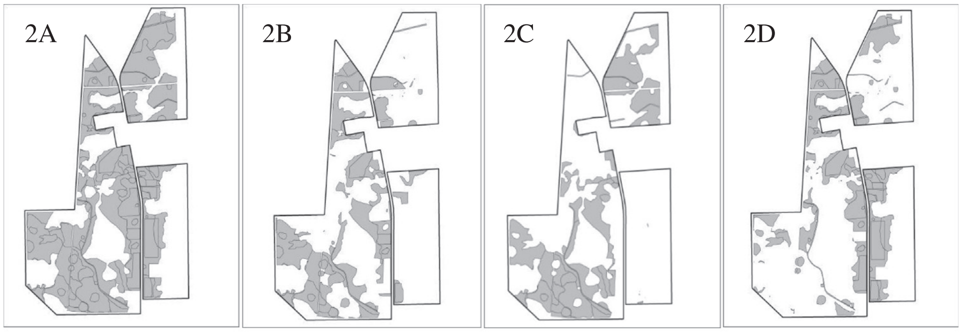
To meet the goal of scenario 3, instead of reducing each of the tree stand age groups by 50%, we analyzed how conserving older tree stands impacted carbon storage and sequestration. Our preliminary analyses indicated that older tree stands stored and sequestered more carbon (Table 4). Tree stands with ages 19–29 and 30–61 yrs were conserved in this scenario (Fig. 2C). This resulted in conserving 89% of stored carbon and 80% of sequestered carbon (Table 5).

3.7. Scenario 4: conserving younger tree stands

To meet the goal of scenario 4, we analyzed how conserving younger trees impacted carbon storage and sequestration. As trees grow, they sequester more carbon but sequestration drops off and eventually trees begin to emit CO_2 as they reach the end of their life cycle (Jo & McPherson, 1995; Nowak, 1993). We wanted to determine how the initial conservation of young trees would affect carbon storage and sequestration, since young trees will eventually mature and replace existing older trees. We conserved trees in age

Table 5
Build design scenarios for the Gainesville 121 site showing the total number of residential units, acres impacted, the amount of carbon storage and sequestration remaining after all vegetation is cleared in the construction area, and percent conserved in CO_2 storage and sequestration from preconstruction values.

Scenario	Residential units	Hectares	Carbon storage (t)	(%) Benchmark conserved	Gross carbon seq. (t/yr)	(%) Benchmark conserved
Benchmark	0	705	29,938	100	2857	100
1	1835	415	16,338	55	1327	46
2	1835	207	23,138	77	2092	73
3	1835	207	26,623	89	2291	80
4	1835	207	20,443	68	1932	68
5	1835	207	25,776	86	2206	77
6	1835	207	27,298	91	2350	82
7	1835	207	23,949	80	2175	76
8	1835	204	24,312	81	2148	75

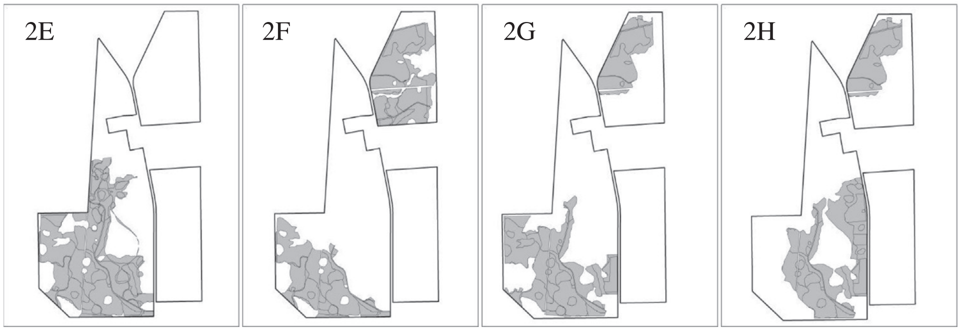


Scenario 1: Permitted Construction

Scenario 2: Reduced Buildable Area

Scenario 3: Conserve Tree Stands > 18 yrs .

Scenario 4: Conserve Tree Stands < 19 yrs.



Scenario 5: Single Compact Design Impacting Existing Conservation Areas

Scenario 6: Multiple Compact Designs Impacting Existing Conservation Areas

Scenario 7: Multiple Compact Designs With No Impact To Conservation Areas

Scenario 8: Compact Designs Within Current Land Use Designations

Fig. 2. (A–H) Gainesville 121 development scenarios, buildable acreage in gray, illustrating change in compactness based on design goals that conserve open space, protect specific tree stand age groups, and working within current designated zoning boundaries.

groups 2–9 and 10–18 yrs (Fig. 2D). This design conserved 68% of stored carbon and 68% of sequestered carbon (Table 5).

3.8. Scenario 5: single compact design

To meet the goal of scenario 5, we placed all built areas into one area and maximized the conservation of older tree stands with ages 19–29 and 30-61 yrs. The compact built area was selected regardless of land use designation and overlapped the largest intact area of young tree stands (2–9 and 10–18 yrs) and an area designated as permitted conservation (Fig. 2E). We placed the developed area near multiple main thoroughfares for easy access and also near existing residential and commercial communities. For this and other compact design scenarios, we wanted to maximize other conservation values such as wildlife habitat and minimize roads built and vehicle miles traveled. Larger conserved areas have less edge, which provides more viable habitat for wildlife species that avoid edge-dominated landscapes (Bollinger & Switzer, 2002; Fletcher, 2005; Marks & Duncan, 2009). This scenario converted 64 ha of conservation area that contained 60 ha of wetlands. This design conserved 86% of stored carbon and 77% of sequestered carbon (Table 5).

3.9. Scenario 6: multiple compact design impacting conservation areas

To meet the goal of scenario 6, we placed buildable space into two compact development areas and maximized conservation of older tree stands with ages 19–29 and 30–61 yrs. As in scenario 5, we ignored permitted land use designations and clustered buildable space in areas that contained younger tree stands (Fig. 2F). This scenario impacted 41 ha of the total land allocated as conservation area; wetlands comprised approximately 37 ha of these areas. This design conserved 91% of stored carbon and 82% of sequestered carbon (Table 5).

3.10. Scenario 7: multiple compact design – no impact to conservation areas

To meet the goal of scenario 7, we kept compact built areas out of the floodplains and wetlands of the designated conservation areas delineated by the City of Gainesville. The previous compact design scenarios (i.e. 5–6) allowed construction to take place in these protected areas and may be undesirable from a city planning or environmental regulation perspective. This scenario looks at a multiple compact design solution that does not impact these conserved areas but does require changing permitted land use designations because the commercial areas had to be placed in residential land uses (Fig. 2G). Again, older tree stands (19–29 and 30–61 yrs) were targeted for conservation. This design conserved 80% of stored carbon and 76% of sequestered carbon (Table 5).

3.11. Scenario 8: compact design within current land use designations

To meet the goal of scenario 8, we explored a compact design following both permitted building and designated conserved areas boundaries (Fig. 2H). Staying within current land use designations, we targeted the largest buildable areas that have young tree stands (2–9 and 10–18 yrs) to determine how compact we could get the design without changing current land use boundaries. There is a slight reduction in buildable area from 207 ha to 204 ha with a corresponding increase in residential density in order to achieve a total of 1835 residential units. This design conserved 81% of stored carbon and 75% of sequestered carbon (Table 5).

4. Discussion and conclusions

4.1. Discussion

On the Gainesville 121 study site, differences in carbon storage and sequestration were more notable between tree stand age groups than between forest types. The older tree stand age groups 19–29 and 30–61 yrs stored more carbon than the younger tree stand age categories 2–9 and 10–18 yrs consistent with previous research showing that stand age is an important variable in determining carbon storage (Timilsina et al., 2013; Wang et al., 2011). Healthy, large trees store several times more carbon than smaller trees, thus even small conservation areas can have significant impacts on a development's overall carbon footprint (Escobedo et al., 2010; Maco & McPherson, 2003; Nowak & Dwyer, 2007). Differences for carbon sequestration mirrored storage results with the exception of the comparison between tree age groups 10–18 yrs and 19–29 yrs showing no significant differences possibly from having similar growth rates and densities (Escobedo et al., 2010; Nowak & Crane, 2002).

Carbon storage and sequestration did not differ among the three forest classes with the exception that the hydric forest type stored more carbon than mesic–hydric. Tree species, diameter, and stand age distributions are important parameters influencing carbon storage and sequestration (Nowak, 1993; Timilsina et al., 2013), and similar carbon values between forest types in this study may be attributed to the fact that this is a heavily managed forest. 68% of the study site was pine plantation and the composition and abundance of tree species was likely not typical of a more natural forest. Both mesic–hydric and xeric–mesic had a large percentage of pine species, 58% and 55% respectively, whereas hydric was much lower at 24%. This indicates that the hydric forest type was not as heavily managed for pine. Further indication of this was that almost 55% of all hydric plots were located in older 30–61 yrs tree stands while only 7% of mesic–hydric plots were in the same age category. In the hydric area large, older trees, mostly oak (*Quercus* spp.), cypress (*Taxodium* spp.), and sweetgum (*Liquidambar styraciflua*) stored most of the carbon, while pine species store the greatest share of carbon in mesic–hydric. Many of the trees in the hydric areas may have been left as seed trees from earlier tree harvests or were left because they had low commercial value. Some of these larger trees may not have been harvested due to the difficultly in reaching and extracting these trees from hydric areas. Thus, greater carbon storage in the hydric forest category was probably a result of decreased harvesting and decreased pine management in these areas.

Analysis of forest type carbon storage and sequestration on a per hectare basis is comparable with previous research in the Gainesville and Miami-Dade regions of Florida (Escobedo et al., 2010). Our gross carbon storage estimates for the Gainesville 121 ranged from 30.9–81.7 t/ha while the other study reported a net storage range of 1.5–74.4 t/ha in Miami-Dade and Gainesville, respectively. In these previous Florida studies, the wide range for results was due to analyses of several additional land use types; these land uses included agricultural, commercial, institutional, residential, and utility, which was not part of the Gainesville 121 study. The findings of the Gainesville 121 study are for gross carbon, while previous work used net carbon values, which have been shown elsewhere to be about 75% of gross values (Nowak & Crane, 2002).

In highly managed pine plantations, focus on conserving older tree stand ages may be an appropriate strategy to maximize carbon storage and sequestration instead of concentrating on conserving areas that have different forest types. However, in a more natural setting or if the landowner does not have tree stand age information, it may be appropriate to conserve more hydric areas because they potentially have the largest carbon storage and sequestration due to the probability of higher nutrient levels that increase growth rates in trees (McConnaughay, Nicotra, & Bazzaz, 1996). In the Gainesville 121 site, although heavily managed, hydric areas had a greater number of older tree stand age categories and the bulk of the carbon storage was made up of other tree species besides *Pinus* spp. An added benefit of conserving hydric forest type may be biodiversity conservation because the hydric areas contained a greater diversity of large trees (see Table 2).

Comparing different subdivision designs, we did find that the placement of built areas could significantly improve carbon storage and sequestration. Three of the top performing scenarios had the potential to conserve over 85% of carbon storage and over 76% of carbon sequestration. This is an increase of over 30% in total carbon benefit from the current permitted design scenario. Of the three top performing scenarios, two have compact designs. Below, we discuss the pros and cons for all scenarios in the context of creating a sustainable development plan that not only reduces the carbon footprint, but also meets other environmental goals such as conserving biodiversity.

Scenarios 2–4 reduced buildable area by 50%, doubled residential density, and stayed within the existing land use boundaries. The 3rd scenario targeted conservation of older tree stands and ranked 2nd in terms of carbon storage and sequestration whereas the scenarios focusing on younger tree stands and reducing built areas by half ranked 6th and 7th in storage and sequestration. All of these scenarios conserved more carbon than the permitted design and benefited from the buildable area being cut in half. Conserving the maximum amount of trees in stand ages 19–29 and 30–62 yrs appears to be a key factor. However, all design scenarios can further reduce the site's overall carbon footprint by implementing sustainable construction practices. In any development, constructing neighborhoods will account for additional tree loss due to infrastructure construction activities. For example, the conserved patches may be exposed to heavy equipment activity, such as earthwork machines being parked or operated through these areas; these activities damage trees and negatively affect tree condition and longevity (Hauer, Miller, & Ouimet 1994). Further, a portion of carbon offsets from tree conservation will be reduced from the input of concrete, a source of CO_2 emissions (United States Environmental Protection Agency, 2010), which will be needed to connect lots in the form of roads and sidewalks. If roads are positioned in a way that increases the length of time to get from point A to point B this will lead to an increase in vehicle miles traveled, a large contributor to CO_2 emissions in cities (Brownstone & Golob, 2009; Glaeser & Kahn, 2010). Transportation account for over 40% of CO_2 emissions in cities (Glaeser & Kahn, 2010; United States Energy Information Administration, 2009).

Overall, compact designs, combined with sustainable construction practices, will minimize a site's overall carbon footprint. Two compact designs (scenarios 5 & 6) provided the best overall conservation of carbon storage and sequestration but negatively impacted designated conservation areas. The single compact design and the multiple compact design rank 3rd and 1st in carbon conservation respectfully. These two scenarios focused on conserving older tree groups 19–29 and 30–61 yrs without sacrificing compactness. There is a broad consensus among researchers that compact city designs and reducing individual carbon footprints are needed in order to mitigate the effects of climate change (Breheny, 1995; Glaeser & Kahn, 2010). The compact designs in this study not only maximizes storage and sequestration by conserving forested areas, it can save a developer or municipality money through reduced capital costs for paved roads.

Scenarios 5 & 6 impacted conserved areas because younger tree stands were marked for development to allow for additional conservation of tree age stands 19–29 and 30–61 yrs. Encroaching upon these areas may or may not be desirable, depending on the biological integrity and functionality of these wetlands over the short and long term. It is not known how pristine these wetlands were, and further analyses is needed to determine if they should or should not be encroached upon to maximize carbon storage and sequestration. Wetlands provide an array of environmental goods and services which include flood control, water/pollutant filtration, nutrient recycling, and aquatic habitat for thousands of species (Keddy et al., 2009; Kusler & Opheim, 1996; Tiner, 1998).

However, wetlands conserved near or surrounded by built areas may not function because of stormwater pollutants from homes and roadways. Thus, saving all wetlands may initially result in higher carbon storage and sequestration values, but this design may have relatively more negative impacts on wetlands than a compact design. For example scenario 3, which had the 2nd highest carbon storage and sequestration, did not impact conserved areas containing wetlands but did increase the possibility that wetlands could be adjacent to or surrounded by, built areas. Urbanization can increase soil erosion, nutrient, and fertilizer runoff into nearby wetlands (Kusler & Opheim, 1996; Tiner, 1998). Stormwater runoff from impervious surfaces can be loaded with nutrients that can be transported rapidly across impervious surfaces to wetlands causing wide fluctuations in water levels and nuisance algae blooms that deplete oxygen levels in water bodies (Hogan & Walbridge, 2007; Kusler & Opheim, 1996). Fluctuations in water flow can affect hydroperiod and water depth thereby changing the flora and fauna associated with wetland ecosystems, frequently lowering species richness (Reinelt, Horner, & Azous, 1998). Built areas that are next to wetland areas can also cause higher levels of mortality for wildlife, especially herpetofauna, with roadways creating barriers to migration and dispersal (Aresco, 2005). The impact of urbanization on local wetlands can vary greatly and is dependent on construction practices and stormwater treatment techniques. That said, the functionality of wetlands, over the long term, was beyond the scope of this study. Additionally, conserving all wetlands can increase fragmentation and the construction of more roads, increasing CO_2 emissions through more pavement and vehicle miles traveled. The practice of conserving all wetland areas does raise the question of whether it is prudent to conserve all wetlands if they lead to a fragmented design. In order to get a more compact design, it may be better to build in some more degraded wetland areas and perhaps use these areas as stormwater retention ponds. This may help other natural wetlands retain their functionality because they are located away from built areas.

From an ecological perspective, any development scenario will have fragmented and undisturbed habitat with varying degrees of impact on local flora and fauna. Fragmented forest landscapes have large amounts of edge due to the abundance of small forest areas that remain post construction. These edges and smaller isolated forest areas can influence flora and fauna populations, dispersal rates and species interactions (Paton, 1994). Along newly created forest edges, an increase in vegetation along with downed trees and snags is usually evident as well as an increase in species richness as shrubs, grasses, and understory tree populations proliferate filling in gaps (Harper et al., 2005). However, near urban developments, these edges are typically dominated by non-native species thereby reducing the number of native species (Kowarik, 2008). Even when revegetation takes place as homeowners move into a development, many times non-native species are typically introduced and then spread into nearby natural areas (McKinney, 2002).

Increases in edge habitat affect wildlife species in both positive and negative ways. Generalist species, such as White-tailed deer (*Odocoileus virginianus*), prefer edge habitat whereas interior forest bird specialists avoid edge habitats (Blake & Karr, 1987; Bolger, Scott, & Rotenberry, 1997; McKinney, 2002). Predators that are generalists seem to flourish with an increase in edge habitat, natural mesopredators such as raccoon (*Procyon lotor*), opossum (*Didelphis virginiana*), and coyote (*Canis latrans*) numbers have increased even with the reduction of natural habitats (Heske, Robinson, & Brawn, 1999). In our study, the compact designs have much less edge than the more fragmented scenarios. This allows for large, intact, forest patches that enhance connectivity and could promote the movement of wildlife (Perault & Lomolino, 2000). Large tracts of land reduce the possibility of anthropogenic disturbance and promote use by specialist species that tend to avoid small patches, which enhances a region's overall species diversity (Blake & Karr, 1987). Expansive areas allow for a more natural home range and additional space for dispersal promoting species richness (Blake & Karr, 1987).

In this study, we assumed that all trees were cleared on buildable areas, but preserving trees on individual built lots can further reduce a development's carbon footprint. Such trees could shade homes and reduce/avoid energy consumption for individual residences and the development as a whole. If trees were preserved in the correct location to shade homes, then energy usage could be reduced and carbon emissions avoided. Previous research in nearby Gainesville, Florida estimated that urban forests offset about 3% of emissions stemming from buildings, transportation, and other human activities in the city (Escobedo et al., 2010). Additional research has shown that energy use in a home with the benefit of tree shading can be 20–25% lower than a home without trees (Heisler, 1986). Conservation of existing trees on built lots, especially large trees, allows for additional carbon storage and sequestration and reduces a home's energy use thereby avoiding additional carbon emissions.

4.2. Conclusions

The combination of future population increase and the shifting of a majority of the populous from rural to urban areas suggest that subdivision design and management will become an important GHG reduction strategy. Through this study we have been able to show that focusing preservation of older tree stands and implementing compact designs can be a viable GHG mitigation strategy. One scenario conserved 91% of existing carbon storage and 82% of current annual sequestration by protecting older aged tree stands. It must be recognized, though, that the study evaluated the carbon storage and sequestration at one point in time. A subdivision's future carbon footprint is dependent on how forest stands and how urban trees are managed over time. For example, thinning of the pine plantation versus not managing the pines and allowing oaks to intrude would result in very different carbon footprints in decades to come. This also holds true on how urban trees are managed; for example, well-maintained large oaks and cypress in conjunction with the removal of diseased trees (with replanting) will increase the storage and sequestration value of a site.

Overall, the clustered design not only benefits carbon storage and sequestration goals, but it has the added co-benefit of conserving biodiversity and minimizing carbon emissions through fewer roads built and fewer miles traveled by vehicles. Although trade-offs occur across various sustainability objectives, city planners and developers can evaluate various community designs and try to balance various objectives. However, other competing interests must be brought into the discussion to weigh the benefits of conserving carbon versus other sustainability objectives. For example, a wildlife corridor may warrant the conservation of areas that have low carbon value. Discussions among various scientists must ensue in order to achieve the optimal design that addresses a variety of sustainability issues. Municipalities should also allow for flexibility in zoning so changes from standard subdivision designs can be replaced with compact designs.

Acknowledgments

We would like to thank Greg Galpin, Katie Glodzik, Allison Megrath, Mario Mighty, Al Zelaya, and the staff members at Plum Creek, the University of Florida's School of Natural Resources and Environment, Wildlife Ecology and Conservation, and the Program for Resource Efficient Communities for their technical support throughout this project.

References

Arendt, R. (1996). *Conservation design for subdivisions: A practical guide to creating open space networks*. Washington, DC: Island Press.

Aresco, M. J. (2005). Mitigation measures to reduce highway mortality of turtles and other herpetofauna at a north Florida lake. *Journal of Wildlife Management*, *69*(2), 549–560. http://dx.doi.org/10.2307/3803725

Blake, J. G., & Karr, J. R. (1987). Breeding birds of isolated woodlots: Area and habitat relationships. *Ecology*, *68*(6), 1724–1734. http://dx.doi.org/10.2307/1939864

Bolger, D. T., Scott, T. A., & Rotenberry, J. T. (1997). Breeding bird abundance in an urbanizing landscape in coastal southern California. *Conservation Biology*, *11*(2), 406–421. http://dx.doi.org/10.1046/j.1523-1739.1997.96307.x

Bollinger, E. K., & Switzer, P. V. (2002). Modeling the impact of edge avoidance on avian nest densities in habitat fragments. *Ecological Applications*, *12*(6), 1567–1575. http://dx.doi.org/10.2307/3099922

Breheny, M. (1995). The compact city and transport energy consumption. *Transactions of the Institute of British Geographers*, *20*(1), 81–101. http://dx.doi.org/10.2307/622726

Brown, S., Swingland, I. R., Hanbury-Tenison, R., Prance, G. T., & Myers, N. (2002). Changes in the use and management of forests for abating carbon emissions: Issues and challenges under the Kyoto Protocol. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, *360*, 1593–1605. http://dx.doi.org/10.2307/3066579

Brownstone, D., & Golob, T. F. (2009). The impact of residential density on vehicle usage and energy consumption. *Journal of Urban Economics*, *65*(1), 91–98. http://dx.doi.org/10.1016/j.jue.2008.09.002

Dobbs, C., Escobedo, F. J., & Zipperer, W. C. (2011). A framework for developing urban forest ecosystem services and goods indicators. *Landscape and Urban Planning*, *99*(3–4), 196–206. http://dx.doi.org/10.1016/j.landurbplan.2010.11.004

Escobedo, F., Varela, S., Zhao, M., Wagner, J. E., & Zipperer, W. (2010). Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities. *Environmental Science & Policy*, *13*(5), 362–372. http://dx.doi.org/10.1016/j.envsci.2010.03.009

Fletcher, R. J. (2005). Multiple edge effects and their implications in fragmented landscapes. *Journal of Animal Ecology*, *74*(2), 342–352. http://dx.doi.org/10.1111/j.1365-2656.2005.00930.x

Florida Fish and Wildlife Conservation Commission. (2003). *Florida land cover*. Gainesville, FL: Florida Geographic Data Library.

Food and Agriculture Organization of the United Nations. (2010). *Global forest resources assessment 2010 (FAO forestry paper 163)*. Rome, Italy: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/docrep/013/i1757e/i1757e.pdf

Geist, H. J., & Lambin, E. F. (2002). Proximate causes and underlying driving forces of tropical deforestation. *BioScience*, *52*(2), 143–150. http://dx.doi.org/10.1641/0006-3568(2002)052[0143:pcaudf2.0.co;2]

Glaeser, E. L., & Kahn, M. E. (2010). The greenness of cities: Carbon dioxide emissions and urban development. *Journal of Urban Economics*, *67*(3), 404–418. http://dx.doi.org/10.1016/j.jue.2009.11.006

Godfrey, R. K. (1988). *Trees, shrubs, and woody vines of northern Florida and adjacent Georgia and Alabama*. Athens, GA: University of Georgia Press.

Harper, K. A., Macdonald, S. E., Burton, P. J., Chen, J., Brosofske, K. D., Saunders, S. C., et al. (2005). Edge influence on forest structure and composition in fragmented landscapes. *Conservation Biology*, *19*(3), 768–782. http://dx.doi.org/10.1111/j.1523-1739.2005.00045.x

Hauer, R. J., Miller, R. W., & Ouimet, D. M. (1994). Street tree decline and construction damage. *Journal of Arboriculture*, *20*(2), 94–97.

Heisler, G. M. (1986). Energy savings with trees. *Journal of Arboriculture*, *12*(5), 113–125.

Heske, E., Robinson, S., & Brawn, J. (1999). Predator activity and predation on songbird nests on forest-field edges in east-central Illinois. *Landscape Ecology*, *14*(4), 345–354. http://dx.doi.org/10.1023/a:1008033603827

Hogan, D. M., & Walbridge, M. R. (2007). Urbanization and nutrient retention in freshwater riparian wetlands. *Ecological Applications*, *17*(4), 1142–1155, 10.2307/40061903.

Hostetler, M. (2012). *The green leap: A primer for conserving biodiversity in subdivision development*. Berkeley, CA: University of California Press.

Hostetler, M., & Drake, D. (2009). Conservation subdivisions: A wildlife perspective. *Landscape and Urban Planning*, *90*(3–4), 95–101. http://dx.doi.org/10.1016/j.landurbplan.2008.10.018

Jo, H.-K. (2002). Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *Journal of Environmental Management*, *64*(2), 115–126. http://dx.doi.org/10.1006/jema.2001.0491

Jo, H.-K., & McPherson, E. G. (2001). Indirect carbon reduction by residential vegetation and planting strategies in Chicago, USA. *Journal of Environmental Management*, *61*(2), 165–177. http://dx.doi.org/10.1006/jema.2000.0393

Jo, H.-K., & McPherson, E. G. (1995). Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management*, *45*(2), 109–133. http://dx.doi.org/10.1006/jema.1995.0062

Kawula, R. (2009). *Florida land cover classification system (final report from State Wildlife Grant, SWG T-13)*. Tallahassee, FL: Florida Fish and Wildlife Conservation Commission.

Keddy, P. A., Fraser, L. H., Solomeshch, A. I., Junk, W. J., Campbell, D. R., Arroyo, M. T. K., et al. (2009). Wet and wonderful: The world's largest wetlands are conservation priorities. *BioScience*, *59*(1), 39–51. http://dx.doi.org/10.1525/bio.2009.59.1.8

Kowarik, I. (2008). On the role of alien species in urban flora and vegetation. In J. Marzluff, E. Shulenberger, W. Endlicher, M. Alberti, G. Bradley, C. Ryan, U. Simon, & C. ZumBrunnen (Eds.), *Urban ecology* (pp. 321–338). New York, NY: Springer US.

Kusler, J., & Opheim, T. (1996). *Our National Wetland Heritage: A protection guide* (2nd ed.). Washington, DC: Environmental Law Institute.

Loewenstein, E. F., Johnson, P. S., & Garrett, H. E. (2000). Age and diameter structure of a managed uneven-aged oak forest. *Canadian Journal of Forest Research*, *30*(7), 1060–1070.

Maco, S., & McPherson, E. G. (2003). A practical approach to assessing structure, function, and value of street tree populations in small communities. *Journal of Arboriculture*, *29*(2), 84–97.

Malhi, Y., Meir, P., & Brown, S. (2002). Forests, carbon and global climate. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, *360*(1797), 1567–1591.

Marks, B. K., & Duncan, R. S. (2009). Use of forest edges by free-ranging cats and dogs in an urban forest fragment. *Southeastern Naturalist*, *8*(3), 427–436. http://dx.doi.org/10.1656/058.008.0305

McConnaughay, K. D. M., Nicotra, A. B., & Bazzaz, F. A. (1996). Rooting volume, nutrient availability, and CO_2-induced growth enhancements in temperate forest tree seedlings. *Ecological Applications*, *6*(2), 619–627. http://dx.doi.org/10.2307/2269396

McKinney, M. L. (2002). Urbanization, biodiversity, and conservation. *BioScience*, *52*(10), 883–890. http://dx.doi.org/10.1641/0006-3568(2002)052[0883:ubac]2.0.co;2

McPherson, E. G., Nowak, D. J., & Rowntree, R. A. (1994). *Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project (general technical report NE-186)*. Radnar, PA: United States Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Milder, J. C. (2007). A framework for understanding conservation development and its ecological implications. *BioScience*, *57*(9), 757–768. http://dx.doi.org/10.1641/b570908

National Oceanic and Atmospheric Administration. (2011). *Local climatological data annual summary with comparative data*. Gainesville, FL: National Oceanic and Atmospheric Administration. From http://www1.ncdc.noaa.gov/pub/orders/IPS-F06D0531-D7D7-4E99-92B8-57B160E43621.pdf

Natural Resources Conservation Service. (2014). *Web soil survey*. (n.d.). Retrieved March 15, 2013 from http://websoilsurvey.nrcs.usda.gov/

Nowak, D. J. (1993). Atmosperic carbon reduction by urban trees. *Journal of Environmental Management*, *37*, 207–217.

Nowak, D. J., & Crane, D. E. (2002). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution*, *116*(3), 381–389. http://dx.doi.org/10.1016/s0269-7491(01)00214-7

Nowak, D. J., Crane, D. E., Stevens, J. C., Hoehn, R. E., Walton, J. T., & Bond, J. (2008). A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture & Urban Forestry*, *34*(6), 347–358.

Nowak, D. J., & Dwyer, J. F. (2007). Understanding the benefits and costs of urban forest ecosystems. In J. E. Kuser (Ed.), *Urban and community forestry in the northeast* (2nd ed., pp. 25–46). New York, NY: Springer.

Paton, P. W. C. (1994). The effect of edge on avian nest success: How strong is the evidence? *Conservation Biology*, *8*(1), 17–26. http://dx.doi.org/10.1046/j.1523-1739.1994.08010017.x

Perault, D. R., & Lomolino, M. V. (2000). Corridors and mammal community structure across a fragmented, old-growth forest landscape. *Ecological Monographs*, *70*(3), 401–422. http://dx.doi.org/10.2307/2657209

Radson, M. J. (2010). *Land use change – commonly known as plum creek (ordinance no. 100189)* Gainesville, FL.

Reinelt, L., Horner, R., & Azous, A. (1998). Impacts of urbanization on palustrine (depressional freshwater) wetlands—research and management in the Puget Sound region. *Urban Ecosystems*, *2*(4), 219–236. http://dx.doi.org/10.1023/a:1009532605918

Slik, J. W. F., Aiba, S.-I., Brearley, F. Q., Cannon, C. H., Forshed, O., Kitayama, K., et al. (2010). Environmental correlates of tree biomass, basal area, wood specific gravity and stem density gradients in Borneo's tropical forests. *Global Ecology and Biogeography*, *19*(1), 50–60. http://dx.doi.org/10.1111/j.1466-8238.2009.00489.x

Soloman, S., Qin, D., Manning, M., Alley, R. B., Bernstsen, T., Bindoff, N. L., et al. (2007). Technical summary. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, & K. B. Averyt, et al. (Eds.), *Climate change 2007: The physical science basis.*

Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Timilsina, N., Escobedo, F. J., Cropper, W. P., Jr., Abd-Elrahman, A., Brandeis, T. J., Delphin, S., et al. (2013). A framework for identifying carbon hotspots and forest management drivers. *Journal of Environmental Management*, *114*(0), 293–302. http://dx.doi.org/10.1016/j.jenvman.2012.10.020

Tiner, R. W. (1998). *In search of swampland: A wetland sourcebook and field guide*. New Brunswick, NJ: Rutgers University Press.

United States Census Bureau. (2011). *Population estimates: City and town totals: Vintage 2011*. Retrieved October 16, 2012 from http://www.census.gov/popest/data/cities/totals/2011/index.html

United States Energy Information Administration. (2009). *Emissions of greenhouse gases in the United States 2008 (DOE/EIA-0573 (2008))*. Washington, DC: United States Energy Information Administration, Department of Energy. Retrieved from http://www.eia.gov/oiaf/1605/ggrpt/pdf/0573(2008).pdf

United States Environmental Protection Agency. (2010). *Human-related sources and sinks of carbon dioxide*. Retrieved November 12, 2010 from http://www.epa.gov/climatechange/emissions/co2_human.html

Wang, S., Zhou, L., Chen, J., Ju, W., Feng, X., & Wu, W. (2011). Relationships between net primary productivity and stand age for several forest types and their influence on China's carbon balance. *Journal of Environmental Management*, *92*(6), 1651–1662. http://dx.doi.org/10.1016/j.jenvman.2011.01.024

Zhang, C., Tian, H., Pan, S., Liu, M., Lockaby, G., Schilling, E. B., et al. (2008). Effects of forest regrowth and urbanization on ecosystem carbon storage in a rural–urban gradient in the Southeastern United States. *Ecosystems*, *11*(8), 1211–1222.

Zhao, M., Escobedo, F., & Staudhammer, C. (2010). Spatial patterns of a subtropical, coastal urban forest: Implications for land tenure, hurricanes, and invasives. *Urban Forestry & Urban Greening*, *9*(3), 205–214. http://dx.doi.org/10.1016/j.ufug.2010.01.008