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# Management and Social Indicators of Soil Carbon Storage in a Residential Ecosystem, Midlothian, VA

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ABSTRACT

Soil carbon storage - defined here as carbon mass per unit ground area - is an important ecosystem service, sequestering carbon that might otherwise exist in atmospheric $CO_2$. Significant attention has focused on the effects that humans have on carbon cycling, but little is known about how human behaviors and attitudes relate to lawn carbon storage. The objectives of this study were to conduct household surveys in concert with soil carbon sampling in a 10-yr-old exurban neighborhood near Richmond, Virginia to quantify differences in soil carbon storage between residential lawns and mixed pine-hardwood forest fragments, and to determine how lawn management and environmental attitudes relate to soil carbon storage. Lawns stored significantly less carbon than forest fragments in the top 10 cm of soils. A significant negative relationship was observed between watering and fertilizer frequency and soil carbon storage, but the goodness-of-fit was sensitive to intra-lawn variability in soil carbon mass. Survey respondents that claimed to be environmentalists stored significantly more carbon and spent one hour less per week managing their lawns, suggesting that environmental attitudes may affect how households manage their lawns and, in turn, the quantity of soil carbon stored in residential soils.

Key words: Soil carbon, carbon sequestration, lawn, human-dominated, residential, management

## INTRODUCTION

Deforestation during land-use conversion is a principal determinant of the carbon balance of the conterminous United States, prompting C emissions of 12 Tg $yr^{-1}$ from 1990-2004 (Woodbury et al. 2007). A substantial fraction of C emissions to the atmosphere in the U.S. is attributed to land-use conversion from forest to residential ecosystems, which increased from 2.5 to 3.1% from 1990-2000 (Nowak et al. 2005). Although disturbance during land-use conversion may cause an initial precipitous decline in soil carbon storage, defined here as soil carbon mass per unit area, post-

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conversion management of residential lawns is hypothesized to prompt recovery of soil carbon storage that in some cases exceeds that of undisturbed forests (Pouyat et al. 2006, Pouyat et al. 2007, Pickett et al. 2008). The proposed mechanism for higher soil carbon in highly productive residential lawn 'ecosystems' is the accumulation of grass derived organic matter (Milesi et al. 2005). Nowhere in the U.S. is land-use conversion from forest to residential habitat more prominent than in the southeastern Piedmont region, which is now experiencing net deforestation for the first time in nearly a century as the region rapidly urbanizes (Polsky et al. 2000).

The amount of soil C stored in residential ecosystems following land-use conversion from forests is determined by the balance of carbon inputs and outputs over time, and carbon storage prior to land-use conversion (Pickett et al. 2008). Humans substantially alter the balance of carbon inputs and outputs through management of residential lawns (Baker et al. 2007). Management regimes that augment lawn net primary production (i.e., growth) and retain grass clippings increase carbon inputs to residential soils (Heckman et al. 2000, Kopp and Guillard 2002, Qian et al. 2003). Effects of common lawn management practices on soil organic matter decomposition and, consequently, carbon outputs via microbial respiration are less certain, but soil disturbance generally causes carbon losses (Kaye et al. 2005).

Despite its probable importance, lawn management at the household scale plays an uncertain role in determining soil carbon storage in residential ecosystems, especially in the understudied, urbanizing Piedmont region of the southeastern U.S. (Kaye et al. 2006, Pataki et al. 2006, Pickett et al. 2008). The Virginia Piedmont is a model location for examining the presently poorly understood consequences of land-use transformation on carbon cycling because urban growth is equal to or greater than that of many areas in the region (Rogers and McCarty 2000). Numerous studies conducted in other geographic regions have quantified carbon storage in soils and other pools within human-dominated ecosystems (Jo and McPherson 1995, Koerner and Klopatek 2002, Nowak and Crane 2002, Kaye et al. 2004, Ziska et al. 2004, Kaye et al. 2005, Milesi et al. 2005, Golubiewski 2006, Groffman et al. 2006, Pouyat et al. 2006). Only a few studies have taken soil carbon analyses a step further by empirically examining soil carbon storage across a range of lawn management intensities (Qian and Follett 2002), or in relation to social indicators that, in human-dominated ecosystems, may be robust integrated predictors of soil carbon properties (Pataki et al. 2006, Pickett et al. 2008). Additionally, educational campaigns that aim to reduce household carbon footprints require knowledge of how residential soil carbon storage relates to human behavior and attitudes. For example, carbon footprint models that predict the carbon signature of households from human behavior are proposed tools for educational outreach and behavior interventions (Dilling et al. 2003, Pataki et al. 2006, Dilling 2007b).

Here, household surveys of lawn management behavior and environmental attitudes were conducted, and soil carbon mass (to 10 cm depth) quantified in lawns and forest fragments of a 10-yr-old exurban neighborhood near Richmond, Virginia to: 1) determine whether soil carbon storage differed between forests and lawns; and 2) identify lawn management, physical, and social indicators of soil carbon mass in a residential ecosystem. An important secondary objective of this work is to examine the feasibility of developing simple models for predicting soil C storage from lawn management practices. The study focuses on an understudied system that is increasingly typical of the Piedmont region of southeastern U.S. in which a planted pine forest with hardwood representation is converted to a residential ecosystem (Polsky et al. 2000). The Piedmont comprises a distinct physiographic region of the U.S. with unique soils, climate, and socio-demographic features, suggesting that soil carbon patterns may differ from those reported by prior studies conducted in other geographic areas. Additionally, this study is among the first to link human management behavior and attitudes to soil carbon storage following land-use conversion from forest to residential lawn.

## METHODS

*Study location*

The study was conducted in an upper-middle class exurban neighborhood located 30 km west of Richmond in Midlothian, VA (zip code 23112). Single family homes >300 $m^2$ were built in the middle to late 1990s on residential parcels ranging from 0.25 to 0.5 ha. Human population density was 6440 $km^2$ with a median household size and annual income of 3.26 and $85,000 USD, respectively, in the year 2000 (United States Census Bureau 2000).

The dominant ecosystem prior to land-use conversion to a suburban residential neighborhood, as indicated by the surrounding forest fragments, was a mature forest typical of the region comprised of planted loblolly pine (*Pinus taeda* L.) and volunteer hardwood competition including oak (*Quercus*), hickory (*Carya*), and maple (*Acer*) genera. Homes within the suburban neighborhood are distributed throughout fragmented forest remnants, which are preserved in common space that is used for recreation (Figure 1). Residential soils are a Creedmoor fine sandy loam on slopes of 0-12 % (USDA 2009). Mean January and July air temperatures are 6.1°C and 25.6°C, respectively, with mean annual air temperatures of 14.3°C and mean annual precipitation of 1115 mm (NOAA 2009).

*Experimental design and household surveys*

The experimental design coupled household surveys of lawn management and environmental attitudes with lawn soil bulk density and carbon sampling in a single neighborhood. To examine impacts of forest conversion to lawns, soils were sampled in residential lawns and adjacent forest fragments distributed throughout the neighborhood. The examination of a single, exurban neighborhood minimized variation in soil properties caused by differences in time since land-use conversion, climate, soil type, parcel size, and household affluence, all of which may constrain soil carbon percent and mass (Pickett et al. 2008).

Sixty household surveys of lawn management behavior and environmental attitudes randomly distributed within the study neighborhood in the autumn of 2008 yielded 33 respondents. Surveys inquired about: a) the application, irrespective of frequency, of soil aeration, lawn clipping retention, raking of detritus, mulch, chemical weed control, chemical pesticides, and seeding; and b) the frequency of mowing, watering, and bagged fertilizer application during the autumn, spring, and summer months. Two additional questions asked respondents to describe their alignment with environmental issues and how many hours per week they work in their lawns during the growing season.


FIGURE 1. Aerial view of the residential neighborhood examined for soil properties in Midlothian, Virginia, 30 km outside of Richmond. The inset ruler is 100 m.

*Soil bulk density and carbon percent and mass*

The O horizon and mineral soil carbon were sampled together to a 10 cm depth during the dormant season of 2008-2009 in 33 residential lawns for which management practices were determined via household surveys, and in 24 randomly selected locations within three large, contiguous forest fragments encompassing the residential areas. Sampling was limited to the top 10 cm since this carbon-rich soil surface pool is likely more sensitive to disturbance, including land-use transformation from forest to lawn, and also is more responsive to subsequent management (Pouyat et al. 2006). To minimize potential bias from recently deposited detritus (e.g., leaf litter, woody debris), fresh litter ($O_i$ horizon) was removed from the surface prior to using a metal corer (3.0 cm diameter) to extract soil from each sampling location. It is important to note that because of composite sampling of O and mineral soils, physiochemical properties reported are a combination of both horizons. In each residential lawn, soil subsamples were collected at three locations 10 m apart along a transect running parallel to each house. As a proxy for local microclimate, aspect and slope were recorded for each soil collection location. Forest soils were collected from locations with no visible disturbances that were > 20 m interior to the forest boundary and within the common area of the neighborhood. Soils were stored at -20°C until processed.

In the laboratory, soils were sieved through a 2 mm mesh screen, remaining roots

TABLE 1. Summary of soil properties (to 10 cm depth) and statistics for lawns (n = 33 lawns) and forest fragment soils (n = 24) in Midlothian, VA.

| Parameter | Lawn | Forest fragment |
|---|---|---|
| Bulk density (g $cm^{-2}$) | 0.92 (0.035)* | 0.41 (0.037)* |
| Percent carbon | 3.85 (0.27)* | 16.54 (1.04)* |
| Carbon mass (kg $m^{-2}$) | 3.30 (1.45)* | 5.50 (1.24)* |

Mean ± 1 standard error, *$P < 0.0001$

were removed, and root-free soil was dried in an oven at 60°C to a constant mass and weighed to obtain bulk density. A portion (~ 10 g) of each soil subsample was ground with a mortar and pestle, weighed, and loss on ignition (450°C for 12 hrs) was used to calculate carbon content assuming a 0.58 C fraction (Pouyat et al. 2002). Soil bulk densities were multiplied by the percent carbon of respective subsamples to calculate soil carbon mass.

*Statistical analysis*

A stepwise model selection procedure was used to determine which lawn management and climate proxy parameters (i.e., aspect and slope) correlate with spatial (inter-lawn) variation in soil carbon mass. Soil subsamples taken from the same lawn were averaged for the analysis. Separate modeling analyses were conducted on lawns with coefficients of variation < 0.25 for soil carbon mass and on all lawns to determine how within-lawn variation affected model explanatory power. Lawn management and climate proxy parameters were retained in the regression model when alpha ≤ 0.15, the default for the stepwise procedure in SAS statistical software (SAS Institute, Cary, NC, USA) and a commonly accepted alpha for regression modeling analysis (Montgomery et al. 2001).

Two-tailed t-tests were used to compare mean bulk density, soil carbon percent, and soil carbon mass between lawn and forest soils. A Wilk-Shapiro Normalilty test revealed that data were normally distributed and required no pre-analysis transformation. ANOVA with LSD was used to assess differences in soil carbon mass among self-ascribed environmental behaviors. All statistical analyses were conducted using SAS v. 9.1.

## RESULTS

*Lawn and forest soil properties*

All residential lawn soil properties surveyed differed significantly from those of forest soils ($P < 0.0001$, Table 1). Forest soil bulk density in the top 10 cm was less than half of that observed in lawns, but soil carbon percent in forest soils was over 4 times greater than that of lawns ($P < 0.0001$, Table 1). This resulted in 67 % greater soil carbon storage in the top 10 cm of forest soils (Table 1).

TABLE 2. Relationships between lawn management practices and orientation, and soil carbon mass (to a depth of 10 cm) in an exurban neighborhood near Richmond, VA. Parameters were selected using a stepwise model procedure ($\alpha = 0.15$).

| Lawn Management Practice or Physical Indicator | Effect on Soil Carbon Mass | Partial $r^2$ | P |
|---|---|---|---|
| 1. Watering frequency during growing season | ↓ | 0.18 | 0.06 |
| 2. Southeast facing orientation of lawn | ↓ | 0.11 | 0.11 |
| 3. Fertilization frequency during | ↓ | 0.10 | 0.11 |

*Lawn management, orientation and soil properties*

Stepwise model selection indicated that soil carbon mass was significantly correlated with the frequency of common lawn management practices, watering ($P$ = 0.06) and fertilization ($P$ = 0.11), and with lawn cardinal orientation ($P$ = 0.11). Higher frequencies of lawn watering and fertilization during the growing season corresponded with lower soil carbon mass in the top 10 cm (Table 2). Lawns that were oriented toward the southeast also had lower soil carbon mass than those facing northwest.

Based on these modeling results, an integrated management and orientation index was developed for predicting inter-lawn variation in soil carbon mass to a 10 cm depth. Discrete points were assigned to lawns with higher watering and fertilization frequencies during the growing season, and to those more closely oriented in the southeastern facing direction (Table 3). Thus, a high index value indicates greater lawn management intensity and an orientation toward a putatively dryer, warmer southeastern face. This index, when fitted against soil carbon mass using an exponential decay function, explained 57 % ($P$ = 0.0006) and 18 % ($P$ = 0.05) of the variation in soil carbon mass among lawns with low within-site variation (C.V. < 0.25) and among all lawns, respectively. Soil carbon mass in the top 10 cm exhibited a rapid decline from 4.5 kg $m^2$ in lawns with low indexes to a near asymptotic low of 2.8 kg $m^2$ in lawns with moderate to high indexes (Figure 2).

*Environmental attitudes and soil carbon mass*

Self-ascribed alignment with environmental issues was a moderate indicator of soil carbon mass (Figure 3). Survey respondents who claimed to be strong environmentalists had lawns with significantly greater soil carbon mass by 0.8 kg $m^{-2}$ and they spent one hour less per week on lawn work than those who said that they agree with environmentalists on most issues. Statistical differences among other respondent categories were not significant (P > 0.1). Only one respondent claimed to not be an environmentalist at all and, because of insufficient replication, was excluded from statistical analysis.

TABLE 3. Point assignments used to calculate lawn management and orientation indexes for individual lawns. Parameters were selected for the index using a stepwise modeling procedure when $\alpha < 0.15$ (see Table 2). Lawn indexes were calculated for each surveyed household by summing points associated with each parameter.

| Parameter | Point assignment |
|---|---|
| Watering frequency during growing season | Never = 0; Monthly = 1; Weekly = 2; Daily = 3 |
| Fertilization frequency during growing season | Equals number of fertilizer applications following manufacturer specification (0 to 4) |
| Cardinal orientation facing lawn | Northwest (270-360º) = 0; Northeast (0-90º), Southwest (180-270º) = 1; Southeast (90-180º) = 2 |
| Total possible points | 9 |

## DISCUSSION

Results from this study show that land-use conversion from forest to lawn significantly reduced carbon storage in the top 10 cm of soil. Forest soil carbon storage reported in this study of 5.5 kg $m^{-2}$ in the top 10 cm is similar to 5 kg $m^{-2}$ reported for a suburban forest in Baltimore (Pouyat et al. 2002). The mean residential lawn soil carbon mass of 3.3 kg $m^{-2}$ in the top 10 cm is somewhat lower than that of other urban and suburban lawns of the eastern U.S. sampled to a 15 cm depth (Pouyat et al. 2002). Pouyat et al. (2009) observed comparable carbon storage in soils of >40-yr-old residential lawns and remnant urban forests of Baltimore city. The present study may have revealed lower soil carbon storage in lawns because land-use conversion from forest to exurban lawns was relatively recent (10 yrs), while older urban lawns of Baltimore have had substantially more time to accumulate carbon. Accumulation of soil carbon occurred for decades following land-use conversion from native habitat to residential lawns or golf course greens located in the arid western U.S. (Qian et al. 2003, Golubiewski 2006).

Results from the present study also indicate that lawn soil carbon storage declined with increasing management intensity. Lawn soil carbon storage in this study was negatively correlated with increased fertilization and watering frequency, and with a more southeastern facing lawn orientation. Empirical studies conducted in golf courses indicate mixed effects of fertilization on soil carbon storage, reporting either no effect (Qian and Follett 2002) or a positive effect (Higby and Bell 1999) of fertilization on soil carbon storage. Modeling studies uniformly predict a net increase in soil carbon storage with management intensification (Bandaranayake et al. 2003, Qian et al. 2003, Milesi et al. 2005). Findings from these empirical and modeling studies provide important quantitative assessments of how management behavior might affect soil

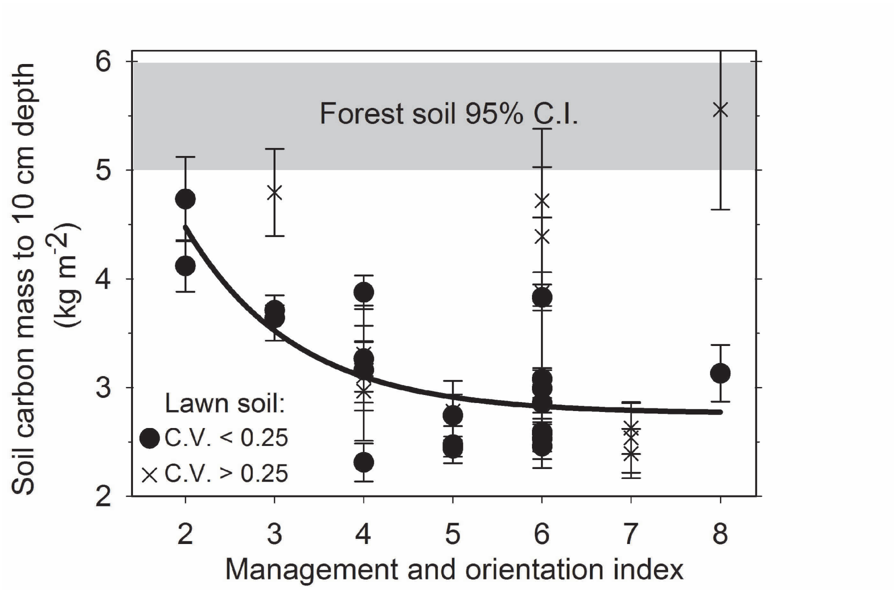


FIGURE 2. Lawn soil carbon mass (to 10 cm depth) in relation to integrated management intensity and lawn orientation indexes (see text and Table 3 for details), and in comparison to soil carbon mass of surrounding forest fragments. A higher index indicates greater lawn management intensity and/or a more southeastern facing orientation. Regression analysis was conducted using mean lawn soil carbon mass values with coefficient of variations (C.V.) < 0.25 (black filled circles; n = 21). Means with C.V. > 0.25 are also shown (black X's; n = 12). Gray-shaded area is the 95 % confidence interval of forest soil carbon mass (n = 24).

carbon storage; however, results from the present study suggest that residential ecosystems, which encompass a range of complex management behaviors, may not uniformly respond to common management practices in the same way.

Declining soil carbon storage with higher fertilization and watering frequency will occur if these parameters cause soil carbon inputs to decrease or carbon outputs to increase. Soil carbon storage decline is unlikely to be caused by a reduction in carbon inputs with fertilizer and water amendments because these supplements typically increase lawn primary production (Higby and Bell 1999, Qian et al. 2003, Milesi et al. 2005). Contrastingly, water and fertilizer amendments may stimulate microbial decomposition of soil organic matter, thereby increasing carbon losses from soils (Kaye et al. 2005, Rodriguez et al. 2005). Although the present study did not detect relationships between aeration and soil carbon storage, tilling and aerating stimulated soil organic matter decomposition in agricultural soils (Reicosky et al. 1997, Kandeler et al. 1999, Paustian et al. 2000). High management intensity in residential ecosystems

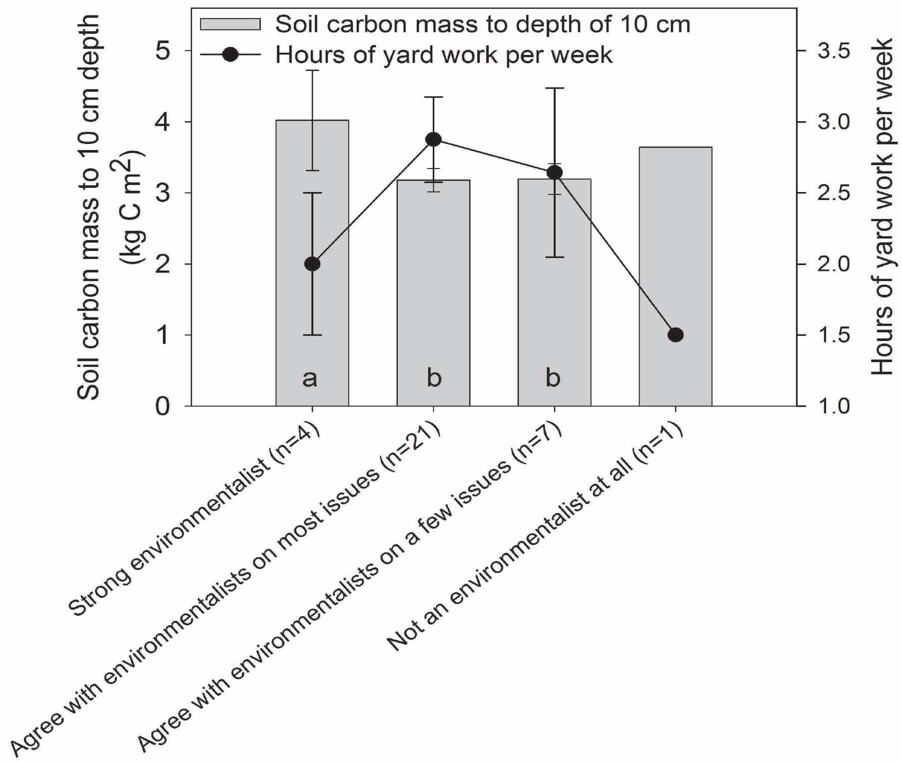


FIGURE 3. Soil carbon mass (10 cm depth) in relation to household views on environmental issues and to hours invested in yard work during the growing season. Survey respondents (n = 33) were asked: "How would you describe yourself with respect to environmental issues?" and "How many hours per week, during the growing season, do you spend caring for your lawn?" Letters indicate significant differences among means ($\alpha = 0.05$).

is a putative cause for elevated microbial activity, and consequently decomposition rates, relative to surrounding natural ecosystems (Green and Oleksyszyn 2002, Koerner and Klopatek 2002, Kaye et al. 2005). In the present study, the mechanistic cause of declining soil carbon with increasing management intensity is unknown, but may be due to enhanced microbial activity. No other management behaviors (e.g., leaving clippings onsite) were significantly correlated with soil carbon storage in the present study and autocorrelation among management behaviors was not detected.

Soil carbon inputs and outputs are also constrained by microclimatic conditions (Bandaranayake et al. 2003, Milesi et al. 2005), which likely varied according to lawn orientation in the present study. Lower soil carbon storage in lawns facing southeast may be caused by dryer, warmer microclimates, which could concurrently reduce net primary production and increase temperature-limited rates of microbial decomposition of organic matter in lawns that are well-watered (Wythers et al. 2005, Del Grosso et al. 2008). Additional investigation is required to quantify the balance of carbon inputs and outputs to residential soils. Particularly, quantitative assessments of carbon outputs are needed for residential ecosystems since most studies have investigated the contribution of carbon inputs to soil carbon storage (Kaye et al. 2006).

Findings from the present study provide novel support for the notion that social indicators can be useful, integrated predictors of soil carbon storage in residential ecosystems. Households that claimed to be more supportive of environmental issues stored significantly more carbon in their lawns (Figure 3), possibly because they spent less time managing their lawns in a way that may reduce soil carbon storage. Strong environmentalists, for example, spent less time managing their lawns and, consequently, watered and fertilized less frequently, behaviors negatively correlated with soil carbon storage in the present study. Results from this study are supported by a limited number of reports that show social indicators are robust predictors of ecosystem properties in human-dominated systems. For example, Tratalos et al. (2007) showed that demographic indicators of social status correlate with residential carbon storage rates in the United Kingdom. Other studies examined how lifestyle behavior or social status relate to parameters known to affect carbon storage, including vegetation cover and tree density (Grove et al. 2006) and fertilizer application rates (Robbins et al. 2001). Qualitative and semi-quantitative social indicators are promising predictors of ecosystem function in human-dominated ecosystems and may be important components of future “carbon footprint” models for urban areas; however, substantial additional research is required to determine which social indicators are the best predictors of residential soil carbon storage and to determine whether management attitudes and behaviors are causally linked (Whitford et al. 2001, Pataki et al. 2006, Grimm et al. 2008).

Results from the current study show that a simple model for estimating soil carbon storage in residential ecosystems may hold future promise, but predictive power is presently limited by unexplained spatial variability in soil carbon mass. High within-lawn variation in soil carbon storage limited the detection of strong statistical relationships with management behavior and orientation when all lawns were included in model development. Soil carbon storage was significantly correlated with the integrated index even when all lawns were included in the regression analysis ($P \leq 0.05$), but this caused a substantial decline in the model’s explanatory capabilities. It is also important to note that this study is of a single neighborhood and, although this approach best addressed study objectives, results are limited in inference to ecosystems with similar social (e.g., economic) and physical (e.g. soils) dimensions. Despite these limitations, this study suggests that the general approach employed herein could be successfully modified to incorporate additional putative explanatory variables that aid in the development of more robust predictive models.

## CONCLUSION

As residential ecosystems grow in number and area, numerous calls have been made to understand how human behavior modifies important ecosystem functions, such as carbon cycling (Vitousek et al. 1997, Pickett et al. 2005, Pataki et al. 2006, Liu et al. 2007, Pouyat et al. 2007, Grimm et al. 2008). Vitousek et al. (1997) asserted that contemporary ecosystem processes cannot fully be understood without investigating how and why humans interact with surrounding ecosystems.

This study is the first conducted in the Piedmont region of the southeastern U.S. to show that household lawn management is a significant predictor of soil carbon storage in residential ecosystems. Further investigation is warranted to evaluate why lawn management intensification decreased lawn soil carbon storage in the present study, a result that departs from some experimental and modeling studies conducted in other geographic regions. A broader understanding of household effects on carbon cycling in residential ecosystems will have implications for ongoing educational campaigns that seek to modify human behaviors that affect greenhouse gas emissions (Dilling 2007a).

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## LITERATURE CITED

Baker, L.A., P.M. Hartzheim, S.E. Hobbie, J.Y. King, and K.C. Nelson. 2007. Effect of consumption choices on fluxes of carbon, nitrogen and phosphorus through households. Urban Ecosystems 10: 97–117.

Bandaranayake, W., Y. L. Qian, W. J. Parton, D. S. Ojima, and R. F. Follett. 2003. Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Pages 558-563.

Del Grosso, S., W. Parton, T. Stohlgren, D. L. Zheng, D. Bachelet, S. Prince, K. Hibbard, and R. Olson. 2008. Global potential net primary production predicted from vegetation class, precipitation, and temperature Ecology 89:2117-2126.

Dilling, L. 2007a. Toward carbon governance: Challenges across scales in the United States. Global Environmental Politics 7:28-44.

Dilling, L. 2007b. Towards science in support of decision making: characterizing the supply of carbon cycle science. Environmental Science & Policy 10:48-61.

Dilling, L., S. C. Doney, J. Edmonds, K. R. Gurney, R. Harriss, D. Schimel, B. Stephens, and G. Stokes. 2003. The role of carbon cycle observations and knowledge in carbon management. Annual Review of Environment and Resources 28:521-558.

Golubiewski, N. E. 2006. Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's front range. Ecological Applications 16:555-571.

Green, D. M., and M. Oleksyszyn. 2002. Enzyme activities and carbon dioxide flux in a Sonoran desert urban ecosystem. Soil Science Society of America Journal 66:2002-2008.

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. G. Wu, X. M. Bai, and J. M. Briggs. 2008. Global change and the ecology of cities. Science 319:756-760.

Groffman, P. M., R. V. Pouyat, M. L. Cadenasso, W. C. Zipperer, K. Szlavecz, I. D. Yesilonis, L. E. Band, and G. S. Brush. 2006. Land use context and natural soil controls on plant community composition and soil nitrogen and carbon dynamics in urban and rural forests. Forest Ecology and Management 236:177-192.

Grove, J. M., A. R. Troy, J. P. M. O'Neil-Dunne, W. R. Burch, M. L. Cadenasso, and S. T. A. Pickett. 2006. Characterization of households and its implications for the vegetation of urban ecosystems. Ecosystems 9:578-597.

Heckman, J. R., H. Liu, W. Hill, M. DeMilia, and W. L. Anastasia. 2000. Kentucky bluegrass responses to mowing practice and nitrogen fertility management. Journal of Sustainable Agriculture 15:25-33.

Higby, J. R., and P. F. Bell. 1999. Low soil nitrate levels from golf course fairways related to organic matter sink for nitrogen. Communications in Soil Science and Plant Analysis 30:573-588.

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

Kandeler, E., D. Tscherko, and H. Spiegel. 1999. Long-term monitoring of microbial biomass, N mineralisation and enzyme activities of a Chernozem under different tillage management. Biology and Fertility of Soils 28:343-351.

Kaye, J. P., I. C. Burke, A. R. Mosier, and J. P. Guerschman. 2004. Methane and nitrous oxide fluxes from urban soils to the atmosphere. Ecological Applications 14:975-981.

Kaye, J. P., P. M. Groffman, N. B. Grimm, L. A. Baker, and R. V. Pouyat. 2006. A distinct urban biogeochemistry? Trends in Ecology & Evolution 21:192-199.

Kaye, J. P., R. L. McCulley, and I. C. Burke. 2005. Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Global Change Biology 11:575-587.

Koerner, B., and J. Klopatek. 2002. Anthropogenic and natural $CO_2$ emission sources in an arid urban environment. Environmental Pollution 116:S45-S51.

Kopp, K. L., and K. Guillard. 2002. Clipping management and nitrogen fertilization of turfgrass: Growth, nitrogen utilization, and quality. Crop Science 42:1225-1231.

Liu, J. G., T. Dietz, S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, and W. W. Taylor. 2007. Complexity of coupled human and natural systems. Science 317:1513-1516.

Milesi, C., S. W. Running, C. D. Elvidge, J. B. Dietz, B. T. Tuttle, and R. R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environmental Management 36:426-438.

Montgomery, D.C., E.A. Peck, and G.G. Vining.2001. Introduction to Linear Regression Analysis. Third Edition. John Wiley & Sons, Inc., New York. 641 p.

NOAA. 2009. Satellite and Information Service. <http://www.ncdc.noaa.gov/oa/climate/stationlocator.html> (March 30, 2009)

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

Nowak, D. J., J. T. Walton, J. F. Dwyer, L. G. Kaya, and S. Myeong. 2005. The increasing influence of urban environments on US forest management. Journal of Forestry 103:377-382.
Pataki, D. E., R. J. Alig, A. S. Fung, N. E. Golubiewski, C. A. Kennedy, E. G. McPherson, D. J. Nowak, R. V. Pouyat, and P. R. Lankao. 2006. Urban ecosystems and the North American carbon cycle. Global Change Biology 12:2092-2102.
Paustian, K., J. Six, E. T. Elliott, and H. W. Hunt. 2000. Management options for reducing $CO_2$ emissions from agricultural soils. Biogeochemistry 48:147-163.
Pickett, S. T. A., M. L. Cadenasso, and J. M. Grove. 2005. Biocomplexity in coupled natural-human systems: A multidimensional framework. Ecosystems 8:225-232.
Pickett, S. T. A., M. L. Cadenasso, J. M. Grove, P. M. Groffman, L. E. Band, C. G. Boone, W. R. Burch, C. S. B. Grimmond, J. Hom, J. C. Jenkins, N. L. Law, C. H. Nilon, R. V. Pouyat, K. Szlavecz, P. S. Warren, and M. A. Wilson. 2008. Beyond urban legends: An emerging framework of urban ecology, as illustrated by the Baltimore Ecosystem Study. Bioscience 58:139-150.
Polsky, C., J. Allard, N. Currit, R. Crane, and B. Yarnal. 2000. The Mid-Atlantic Region and its climate: past, present, and future. Climate Research 14:161-173.
Pouyat, R., P. Groffman, I. Yesilonis, and L. Hernandez. 2002. Soil carbon pools and fluxes in urban ecosystems. Environmental Pollution 116:S107-S118.
Pouyat, R. V., I. D. Yesilonis, and D. J. Nowak. 2006. Carbon storage by urban soils in the United States. Journal of Environmental Quality 35:1566-1575.
Pouyat, R. V., I. D. Yesilonis, J. Russell-Anelli, and N. K. Neerchal. 2007. Soil chemical and physical properties that differentiate urban land-use and cover types. Soil Science Society of America Journal 71:1010-1019.
Pouyat, R.V., I.D. Yesilonis, and N.E. Golubiewski NE. 2009. A comparison of soil organic carbon stocks between residential turf grass and native soil. Urban Ecosystems. 12:45–62
Qian, Y. L., W. Bandaranayake, W. J. Parton, B. Mecham, M. A. Harivandi, and A. R. Mosier. 2003. Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics: The CENTURY model simulation. Journal of Environmental Quality 32:1694-1700.
Qian, Y. L., and R. F. Follett. 2002. Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data. Agronomy Journal 94:930-935.
Reicosky, D. C., W. A. Dugas, and H. A. Torbert. 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. Soil & Tillage Research 41:105-118.
Robbins, P., A. Polderman, and T. Birkenholtz. 2001. Lawns and toxins - An ecology of the city. Cities 18:369-380.
Rodriguez, I. R., L. B. McCarty, J. E. Toler, and R. B. Dodd. 2005. Soil CO2 concentration effects on creeping bentgrass grown under various soil moisture and temperature conditions. Hortscience 40:839-841.
Rogers, C. E., and J. P. McCarty. 2000. Climate change and ecosystems of the Mid-Atlantic Region. Climate Research 14:235-244.
Tratalos, J., R. A. Fuller, P. H. Warren, R. G. Davies, and K. J. Gaston. 2007. Urban form, biodiversity potential and ecosystem services. Landscape and Urban Planning 83:308-317.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human domination of Earth's ecosystems. Science 277:494-499.

United States Census Bureau. 2000. American Fact Finder. <http://factfinder.census.gov/home/saff/main.html?_lang=en> ( March 30, 2009)

USDA Natural Resources Conservation Service. 2009. Web Soil Survey. <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm> (March 30, 2009)

Whitford, V., A. R. Ennos, and J. F. Handley. 2001. "City form and natural process" - indicators for the ecological performance of urban areas and their application to Merseyside, UK. Landscape and Urban Planning 57:91-103.

Woodbury, P. B., L. S. Heath, and J. E. Smith. 2007. Effects of land use change on soil carbon cycling in the conterminous United States from 1900 to 2050. Global Biogeochemical Cycles 21.GB3006, doi:10.1029/2007GB002950.

Wythers, K. R., P. B. Reich, M. G. Tjoelker, and P. B. Bolstad. 2005. Foliar respiration acclimation to temperature and temperature variable Q(10) alter ecosystem carbon balance. Global Change Biology 11:435-449.

Ziska, L. H., J. A. Bunce, and E. W. Goins. 2004. Characterization of an urban-rural $CO_2$/temperature gradient and associated changes in initial plant productivity during secondary succession. Oecologia 139:454-458.