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Carbon Storage by Urban Soils in the United States

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ABSTRACT

We used data available from the literature and measurements from Baltimore, Maryland, to (i) assess inter-city variability of soil organic carbon (SOC) pools (1-m depth) of six cities (Atlanta, Baltimore, Boston, Chicago, Oakland, and Syracuse); (ii) calculate the net effect of urban land-use conversion on SOC pools for the same cities; (iii) use the National Land Cover Database to extrapolate total SOC pools for each of the lower 48 U.S. states; and (iv) compare these totals with aboveground totals of carbon storage by trees. Residential soils in Baltimore had SOC densities that were approximately 20 to 34% less than Moscow or Chicago. By contrast, park soils in Baltimore had more than double the SOC density of Hong Kong. Of the six cities, Atlanta and Chicago had the highest and lowest SOC densities per total area, respectively (7.83 and 5.49 kg m^{-2}). On a pervious area basis, the SOC densities increased between 8.32 (Oakland) and 10.82 (Atlanta) kg m^{-2}. In the northeastern United States, Boston and Syracuse had 1.6-fold less SOC post- than in pre-urban development stage. By contrast, cities located in warmer and/or drier climates had slightly higher SOC pools post- than in pre-urban development stage (4 and 6% for Oakland and Chicago, respectively). For the state analysis, aboveground estimates of C density varied from a low of 0.3 (WY) to a high of 5.1 (GA) kg m^{-2}, while belowground estimates varied from 4.6 (NV) to 12.7 (NH) kg m^{-2}. The ratio of aboveground to belowground estimates of C storage varied widely with an overall ratio of 2.8. Our results suggest that urban soils have the potential to sequester large amounts of SOC, especially in residential areas where management inputs and the lack of annual soil disturbances create conditions for net increases in SOC. In addition, our analysis suggests the importance of regional variations of land-use and land-cover distributions, especially wetlands, in estimating urban SOC pools.

In terrestrial ecosystems and at global scales soil organic carbon (SOC) is primarily a function of the average net primary productivity (or inputs of organic matter) and the rate of organic matter decay (Kirschbaum, 2000). Because rates of organic matter input and decay differentially vary in their sensitivities to temperature and precipitation, a wide variation in SOC exists among life zones (Post et al., 1982). While precipitation and temperature are good predictors of SOC pools at global scales, pools at regional and local scales vary due to soil drainage and the quality of litter entering the soil system (Berg and McClaugherty, 1987; Côuteaux et al., 1995). These factors in turn are highly related to topography, soil texture, and plant species composition. In urban landscapes, SOC also may vary due to introductions of human disturbances, exotic plants, horticultural management (e.g., fertilization, irrigation, clipping), and urban environmental factors (e.g., urban heat island, elevated atmospheric carbon dioxide). The net result is an "urban soil mosaic" where soil conditions, and thus SOC, can vary widely between and within types or patches of soil (Pouyat et al., 2003).

Recent research efforts have addressed whether various land-use changes and their associated soil modifications will affect soil C storage at regional and global scales (Houghton et al., 1999; Caspersen et al., 2000). In the case of urban land-use change, very little data are available to assess the spatial variation of SOC pools and whether urban land use leads to a net increase or decrease in these pools (Pouyat et al., 2002). This lack of data has made it problematic to predict or assess the regional effects of land-use change on soil C pools in populated regions of the world (e.g., Ames and Lavkulich, 1999; Tian et al., 1999).

In the United States, the conversion of agricultural, grass, and forest land to urban land use is occurring at accelerated rates. Between 1980 and 2000 alone, land devoted to urban uses grew by more than 34% in the United States (USDA Natural Resources Conservation Service, 2001). By contrast, the population grew by only 24% during the same period (United States Department of Commerce, 2001). The resultant urban growth pattern is more dispersed than earlier development patterns and as a result is increasingly affecting the storage of carbon in soils. Urban development can increase or decrease SOC pools depending on the net effect of the previously mentioned factors and the amount of SOC stored in the ecosystem before urban development (Pouyat et al., 2003).

In earlier attempts, we calculated urban SOC pools for the conterminous United States (Pouyat et al., 2002, 2003), but did not consider regional differences in native soils (associated with remnants of native ecosystems) and differences in land-use and vegetative cover patterns that occur among cities (Nowak et al., 1996). In this paper we use data that is available from the literature and our own measurements to estimate SOC pools of cities previously assessed for aboveground carbon stocks by trees (Nowak and Crane, 2002), and use the National Land Cover Database (NLCD) to extrapolate total SOC pools by state, region, and the conterminous United States. Specifically, our objectives were to (i) assess inter-city variability of SOC pools (1-m depth) of six cities (Atlanta, Baltimore, Boston, Chicago, Oakland, and Syracuse) where field collected data of tree biomass, land use, and cover were available; (ii) for the same cities calculate the net effect of urban land-use conversion

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Abbreviations: NLCD, National Land Cover Database; SOC, soil organic carbon.

on SOC pools; (iii) use the NLCD to extrapolate total SOC pools (1-m depth) for each of the lower 48 states, by region, and for the United States (lower 48 states); and (iv) compare these SOC totals with aboveground carbon storage by urban trees.

MATERIALS AND METHODS

Soil Organic Carbon Estimates

Pouyat et al. (2002, 2003) reported on urban SOC data compiled from the literature. Data were required to be to a 1-m depth, sampled by horizon, and measurements made of horizon thickness, percentage of coarse fragments, bulk density, and organic carbon concentration. Only a few studies of urban areas met these requirements. These included data sets from Short et al. (1986), Jo and McPherson (1995), Jim (1998), Stroganova et al. (1998), Evans et al. (2000), and Hernandez et al. (1997). In Pouyat et al. (2002, 2003), pedon data from these studies were assigned into made, park use, recreational, and residential categories. The made-soil category was further subdivided based on the origin of the fill material (clean fill, construction debris, coal ash, refuse, old dredge, and recent dredge materials).

In this paper, we also included preliminary SOC data from Baltimore collected using undisturbed cores. The core method is less intrusive than excavating a pit and allows for more replications at each location. For this study we included 20 sampling locations randomly stratified by land use and land cover from residential (n = 18) and park use (n = 2) grass-cover types within Baltimore. The locations coincided with 0.04-ha circular plots that were sampled for vegetation and surface soils in previous studies (Nowak et al., 2004; Pouyat et al., unpublished data). In each plot we extracted three 3.3-cm-diameter cores (1-m depth) in a triangle at least 1.5 m apart around an approximated center point of the dominant cover type (at least 60% of the plot area). Each core was brought to the lab for characterization and subsampled by horizon. For each horizon, bulk density was measured using the clod method (Blake and Hartge, 1986). The proportion of coarse fragments was determined by passing a known weight of the same subsample through a 2-mm sieve. Subsamples of soil were analyzed for total organic C using a Model 2400 CHNS Analyzer (PerkinElmer, Wellesley, MA). The samples were first ground and passed through a 2-mm sieve and subsequently pulverized by continuously rotating subsamples of soil in glass bottles containing steel rods for at least 24 h.

For all data, the density of C in a horizon of unit area (1 m^2) was calculated as:

$$c = f_C D_b(1 - \delta_{2mm})V$$

where c is carbon density, δ_{2mm} is the fraction of material larger than 2 mm in diameter, D_b is bulk density, f_C is the fraction by mass of organic C, and V is the volume of individual horizons (Post et al., 1982). Data for the soil horizons were summarized to report soil C density on a m^2 basis to a 1-m depth. In those cases where we were unable to extract a core to 1 m, we extrapolated the lowest horizon's measurements to reach a 1-m depth. With these extrapolations we found no relationship between overall SOC density and the difference in length between the actual depth of the core and 1 m.

We combined pedon and core data compiled from the literature and data collected in Baltimore to update estimates of urban SOC densities made in Pouyat et al. (2003) (Table 1). We included SOC estimates only for those urban soil types that corresponded to land-use and land-cover designations for the six cities and the NLCD (i.e., residential grass, park use and grass, and clean fill). Therefore, estimates of SOC for the land-use and land-cover types were not based on a statistical sample but rather on a compilation of data from separate sources. Thus, we make what we consider a best estimate of urban SOC pools with the following assumptions. First, estimates of SOC densities for clean fill, park use, and residential soils are representative of all made soils. We based this assumption on data presented in Pouyat et al. (2002, 2003), which showed that the variance of SOC densities was relatively low at 3.8 ± 0.99 and 15.5 ± 1.2 kg m^{-2} for clean fill and residential soils, respectively. The second assumption is that soils have reached similar steady state equilibriums between C accumulation and decay post-urbanization regardless of region. The third assumption is that SOC pools are negligible below 1-m depth, which underestimates SOC for fill soils in which a buried A horizon exists.

Table 1. Soil organic carbon (SOC) densities for disturbed and made soils in the cities of Baltimore, MD; New York, NY; Chicago, IL; Hong Kong, China; and Moscow, Russia. Except where indicated, carbon densities were calculated with data collected from soil pit or core characterizations to a depth of 1 m (n = number of locations).

Location	Type or land use	Carbon density Mean	SEM	n
		— kg m^{-2} —		
Kings, NY†	clean fill	3.8	0.2	4
Washington, DC‡	clean fill	1.5	0.0	3
Richmond, NY†	clean fill	4.6	0.7	3
Hong Kong, China§	park use and grass	4.2	0.4	5
Baltimore, MD	park use and grass	9.9	0.8	2
Baltimore, MD	residential grass	12.2	1.1	18
Moscow, Russia¶	residential grass	14.6	1.2	2
Chicago, IL#	residential grass	16.3	1.6	2

† Data from New York City Soil Survey, Natural Resources Conservation Service.
‡ Calculated from data reported in Short et al. (1986).
§ Calculated from data reported in Jim (1998).
¶ Calculated from data reported in Stroganova et al. (1998).
# Calculated to a depth of 60 cm from data reported in Jo and McPherson (1995).

Estimation of Individual Cities

Using these data we assigned a SOC density value to previously delineated land-use and land-cover designations to estimate belowground SOC stocks in six cities where such data exist (Table 2). In these cities, urban forest structure was previously determined using methods developed by the USDA Forest Service (Nowak and Crane, 2000). In each city approximately 200 0.04-ha plots were stratified randomly by land use and land cover, and data collected on location, species, stem diameter at 1.37 m above ground (diameter at breast height, dbh), tree and crown height, crown width, canopy location, and the proportion of impervious area. From these data, we calculated the pervious cover for each land-use and land-cover type. We assumed that soils beneath impervious cover had a SOC density of 3.3 ± 0.93 kg m^{-2} or the concentration of SOC found in clean fill (Fig. 1). In the case of remnant soils (undisturbed soils associated with native cover types) we assigned from the literature a SOC density of the representative native soil (Table 2). To calculate the amount of SOC (kg) in each land-use and land-cover type within a city, we multiplied the impervious and pervious areas in Table 3 by 3.3 kg m^{-2} and the densities in Table 2 (residential, park use, and remnant), respectively.

In addition to the previous estimates, we compared the area-weighted SOC density and total amount of SOC of the six cities to SOC levels in the native forest, grass, or agricultural soil that

Table 2. Estimated soil organic carbon (SOC) densities by land use and land cover for each city. Land-use and land-cover type are not consistent across cities due to availability of data.

	City					
Land use or cover	**Atlanta**	**Baltimore**	**Boston**	**Chicago**	**Oakland**	**Syracuse**
	kg m^{-2}					
Agriculture	–	–	6.0†	3.2‡	–	–
Barren	–	3.3§	–	–	–	–
Commercial–industrial	3.3	3.3	3.3	3.3	3.3	3.3
Forest	7.7¶	11.6#	–	–	–	–
Green space	–	–	–	–	–	16.2††
Institutional—vegetation dominated	–	–	–	7.1‡‡	–	–
Institutional—building dominated	–	–	–	3.3	–	–
Institutional	3.3	3.3	–	–	3.3	3.3
Miscellaneous	–	–	–	–	3.3	–
Park	7.1	–	–	–	–	–
Residential	14.4§§	14.4	14.4	14.4	14.4	14.4
Transportation	3.3	3.3	3.3	3.3	3.3	3.3
Urban open	–	3.3	7.1	–	–	–
Vacant	3.3	–	–	5.2¶¶	–	3.3
Wildland	–	–	–	–	5.7##	–
Impervious	3.3	3.3	3.3	3.3	3.3	3.3

† SOC for Northeast cropland (Birdsey, 1992).
‡ SOC for Central cropland (Birdsey, 1992).
§ Average of clean fill values from Table 1 ($n = 3$). This value is used for other land-use and land-cover categories such as commercial–industrial, institutional—building dominated, institutional, miscellaneous, transportation, urban open, vacant, and impervious.
¶ SOC for Southeast timberland (Birdsey, 1992).
# SOC for Mid-Atlantic timberland (Birdsey, 1992).
†† SOC for Northeast timberland (Birdsey, 1992).
‡‡ Average of park use and grass values from Table 1 ($n = 2$).
§§ Average of residential grass values from Table 1 ($n = 3$).
¶¶ SOC for Central grassland (Birdsey, 1992).
SOC for Pacific Coast grassland (Birdsey, 1992).

was likely present before the development of each city. For each city we estimated the SOC density of the native and agricultural soil type using data from Birdsey (1992). In each case, we took the original estimates of SOC pools and densities for each city and compared them with agricultural and native soil type densities for that region of the conterminous United States (Table 2). For example, the Baltimore landscape was previously dominated by hardwood deciduous forests with smaller areas of riparian and wetland soils (Schneider, 1996). After European colonization and before the development of the city, the forested areas were transformed to agricultural uses. We therefore compared current SOC pools and densities with agricultural and forested soil levels that are typical for this region (Table 2).

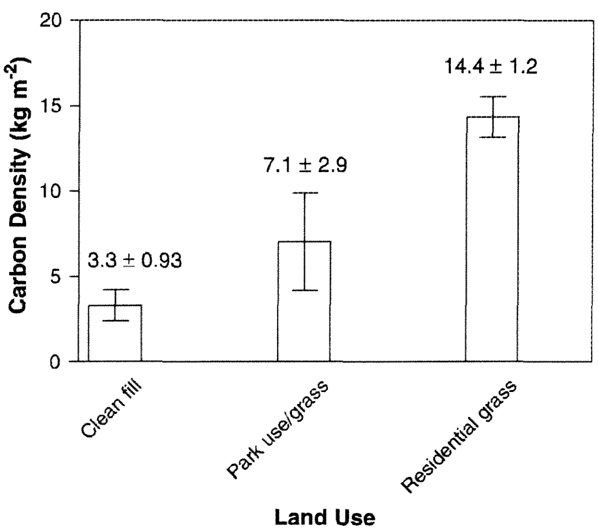

Fig. 1. Means (±SE) of soil organic carbon (SOC) densities (kg m^{-2}) for residential grass ($n = 3$, where n is the number of individual cities), clean fill ($n = 2$), and park use and grass ($n = 2$) soils. Data are summarized from Table 1.

Estimations by State

To estimate SOC pools in urban areas of the conterminous United States, we used the 30-m spatial resolution NLCD to determine urban land-use and land-cover distributions by state (Table 4). In the NLCD, land with a population density of at least 386 people km^{-2} was considered an urbanized area and adjacent places with a minimum population of 2500 people were called urban places; urbanized areas and urban places together comprise urban land (Dwyer et al., 2000; Nowak et al., 2001). Similar to the city estimates above, we assigned our best estimates of SOC densities to individual land-use and land-cover classes within regions (Table 5), and multiplied by the estimated pervious and impervious aerial coverage of these classes for each state. Densities of SOC were derived by multiplying a state's percentage of urban land use and land cover in Table 4 by total urban areas of that state in Table 9. Values were adjusted for impervious cover in each class based on national average estimates of impervious areas within each land-use and land-cover class by Nowak et al. (1996). We then compared the ratio of each state's SOC pool estimations with aboveground carbon stocks (Nowak and Crane, 2002). These data were then summarized for eight U.S. regions after Birdsey (1992). Using this approach, differences in total SOC among states and regions will not only be due to regional differences in urban land use and land cover but also non-urban cover types remaining in the urban landscape (Forest, Grassland, Shrubland, and Agriculture land-use and land-cover classifications in the NLCD) and their assigned SOC densities (Table 5).

RESULTS AND DISCUSSION

Estimates of SOC densities of disturbed and made soils varied widely by land use and land cover (Table 1).

Table 3. Estimates of pervious and total area of land use and land cover by city, calculated using field measurements described in Nowak and Crane (2002).

	City											
	Atlanta	Baltimore	Boston	Chicago	Oakland	Syracuse	Atlanta	Baltimore	Boston	Chicago	Oakland	Syracuse
Land use or cover	Pervious area						Pervious and impervious area					
	ha											
Agriculture	–	–	69	178	–	–	–	–	70	189	–	–
Barren	–	203	–	–	–	–	–	204	–	–	–	–
Commercial–industrial	1191	1719	625	4859	134	299	5898	4996	2207	15493	1542	1034
Forest	4465	1496	–	–	–	–	4474	1698	–	–	–	–
Green space	–	–	–	–	–	638	–	–	–	–	–	728
Institutional—vegetation dominated	–	–	–	2901	–	–	–	–	–	5342	–	–
Institutional—building dominated	–	–	–	1284	–	–	–	–	–	2777	–	–
Institutional	445	796	–	–	752	345	1112	1859	–	–	1313	494
Miscellaneous	–	–	–	–	34	–	–	–	–	–	36	–
Park	1721	–	–	–	–	–	1856	–	–	–	–	–
Residential	11574	4602	2362	10966	2571	1494	18637	10062	6293	29293	5791	3251
Transportation	800	323	728	3280	842	300	1747	594	1644	6690	1932	435
Urban open	–	1226	2797	–	–	–	–	1503	4066	–	–	–
Vacant	361	–	–	1073	–	405	416	–	–	1584	–	559
Wildland	–	–	–	–	2549	–	–	–	–	–	2628	–

The Baltimore residential grass data (n = 18) that was added to the previous data set (Pouyat et al., 2003) had SOC densities that were approximately 20 to 34% less than that of Moscow (n = 2) and Chicago (n = 2), respectively. By contrast, park SOC densities in Baltimore (n = 2) were more than double that was found for grass areas in parks of Hong Kong (n = 5).

Residential grass data from Denver–Boulder, CO (Golubiewski and Wessman, 2006) were available, but the depth of analysis in that study was only 0 to 30 cm. Lawn areas of 40- to 50-yr-old subdivisions were sampled using a core method and had SOC densities of up to 6.2 kg m^{-2}. If we extrapolate C densities to a 30- to 100-cm depth using the lower portion of the core data reported (20–30 cm), we estimate the SOC density would be approximately 11.0 kg m^{-2} for these soils. This estimate is somewhat lower than the residential soils in Table 1, which may reflect the study site (short grass prairie), site history, or the inaccuracy of our 30- to 100-cm depth estimate.

Regardless of the variability in the residential data, it appears that measurements of SOC densities for residential lawns are relatively high and of low variability compared to other non-wetland soil types found in urban landscapes (Fig. 1), which is consistent with a more limited data set in Pouyat et al. (2002). Based on this narrow dataset, residential, clean fill, and park use soils have errors (SE of the mean) of approximately 14.4 ± 1.2, 3.3 ± 0.93, and 7.1 ± 2.9 kg m^{-2}, respectively (Fig. 1). Pouyat et al. (2003) suggested that high SOC densities in residential areas are likely due to the longer growing seasons of cool season turf grasses in comparison to deciduous trees and to increases in net primary productivity from fertilizer and water supplements. The relatively low variability of SOC densities in residential lawns may reflect efforts by individual homeowners to overcome natural constraints on plant growth (and thus decay) irrespective of the prevailing climate and variability of site conditions (Pouyat et al., 2006). By contrast, park-use soils, which did not include highly managed turf areas (e.g., golf courses), were less managed and had greater intensities of use than residential lawns and thus have SOC densities that are more likely to reflect variations in site conditions and use.

City Estimates

Of the six cities analyzed, Atlanta and Chicago had the highest and lowest SOC densities, respectively (7.8 and 5.5 kg m^{-2}) (Table 6). Atlanta's relatively high SOC density can be attributed to the high proportion of forested (13%) and residential areas (55%) in that city (Table 3). Chicago, conversely, had a high proportion of land under impervious cover (60%) and commercial–industrial land uses (25.2%) (Tables 3 and 6). The SOC density of all six cities was 6.3 kg m^{-2} (Table 6). This density value is approximately 25% lower than that of our previously estimated SOC density for urban areas of the conterminous United States (Pouyat et al., 2003). The calculation of SOC density for the six cities is an underestimate since wetlands, which have the potential to store a high amount of SOC (Trettin and Jurgensen, 2003), were not delineated in the previous forest structure analyses.

When SOC densities were calculated by the pervious areas of each city, the densities varied between 8.3 and 10.8 kg m^{-2} for Oakland and Atlanta, respectively (Table 6). The reporting of densities by pervious area resulted in increases of up to 59.9% (Chicago), which we attribute to the relatively low SOC density assigned to soils beneath impervious surfaces (Table 2). Since Atlanta has a relatively low proportion of impervious cover (39.8%), the gain in SOC density on a pervious basis (38.2%) was lower than the other cities. Oakland, on the other hand, while ranking intermediate to the other cities in impervious cover, ranked the lowest in SOC densities on a pervious area basis (Table 6). We attribute this disproportionately small gain in density to Oakland's relatively high proportion of wildland cover, which is associated with low SOC densities characteristic of native soils in the region (Table 2).

Table 4. State percentage of urban land use and land cover based on the National Land Cover Database (NLCD).

	Land use									
State	Agriculture	C–I–T†	Forest	Grassland	Other‡	Park	Residential	Shrubland	Wetlands	Open water
	%									
AL	11	1	57	11	1	4	7	0	4	3
AR	13	2	39	21	0	3	16	0	2	3
AZ	13	2	6	7	2	2	9	57	0	0
CA	4	3	14	22	5	3	22	24	0	3
CO	7	3	5	41	0	7	25	8	0	3
CT	3	4	42	2	1	7	27	0	9	6
DC	0	8	29	0	0	11	35	0	1	16
DE	15	4	30	12	1	5	20	0	7	6
FL	3	3	15	6	5	4	29	1	18	17
GA	6	3	56	4	3	4	15	0	6	2
IA	32	4	11	15	0	8	22	0	3	5
ID	23	5	2	28	0	2	15	21	1	2
IL	18	4	16	12	0	13	27	0	3	5
IN	27	5	14	17	0	8	24	0	2	3
KS	15	5	10	26	1	11	26	0	2	3
KY	11	2	37	25	1	6	15	0	2	3
LA	10	3	23	11	0	6	20	0	15	12
MA	2	3	45	1	1	5	24	0	10	9
MD	6	3	40	18	3	4	17	0	3	7
ME	14	2	59	2	1	3	7	0	5	8
MI	17	5	28	8	1	6	24	0	6	7
MN	13	2	22	13	2	7	17	0	14	9
MO	10	5	24	21	1	14	20	0	2	3
MS	12	2	36	14	1	6	15	0	10	4
MT	2	1	40	39	1	1	2	12	1	1
NC	9	4	48	4	1	3	22	0	5	3
ND	25	6	3	22	0	16	22	1	2	3
NE	21	9	3	20	0	16	28	0	1	2
NH	7	3	64	2	1	2	10	0	6	5
NJ	3	2	36	6	0	3	31	0	10	8
NM	5	3	5	36	2	1	11	35	0	1
NV	0	2	6	13	5	1	8	62	0	2
NY	3	3	36	7	0	7	32	0	2	9
OH	16	4	30	14	0	5	24	0	3	3
OK	14	2	20	47	0	1	12	1	0	3
OR	3	6	28	19	2	4	23	9	1	6
PA	3	3	50	17	2	2	19	0	1	4
RI	1	3	36	1	1	9	27	0	11	11
SC	8	3	42	3	3	4	19	0	9	9
SD	12	4	8	33	1	11	20	2	2	7
TN	8	2	49	15	1	6	14	0	2	3
TX	8	3	20	30	1	3	17	7	4	6
UT	5	3	7	33	2	5	15	29	1	1
VA	6	4	40	13	3	2	17	0	7	7
VT	14	4	40	5	1	2	10	0	7	16
WA	4	4	32	12	2	2	22	13	1	8
WI	24	3	18	15	0	9	20	0	3	7
WV	2	3	57	15	1	1	15	0	0	7
WY	2	2	2	28	1	3	19	42	2	1

† Commercial–industrial–transportation.
‡ "Other" category includes bare rock/sand/clay; quarries/strip mines/gravel pits; transitional; and orchards/vineyards/other.

The SOC densities based on pervious areas of the six cities (8.3–10.8 kg m^{-2}) are high compared to soils of other life zones of the world (Post et al., 1982). The relatively high densities in these cities suggest that urban soils have the potential to store a considerable amount of carbon, particularly in arid climates where net primary productivity and decay rates are limited by the availability of water, but with irrigation can support highly productive ecosystems (Pouyat et al., 2006; Hope et al., 2003). Likewise, aboveground C stocks are also comparable to non-urban ecosystems when reported on pervious area basis. The cities of Atlanta, Baltimore, and Syracuse have up to a 3.5-fold higher amount of aboveground biomass per ha than the other cities including impervious areas (Table 6). However, if we compare pervious areas only, these differences narrowed as Chicago, Boston, and Oakland almost tripled the amount of aboveground biomass while the other cities increased by roughly 88% or less (Table 6). The pervious aboveground densities for some cities approached or exceeded the densities reported for forest lands in the United States. In the case of Atlanta, the aboveground C density on a pervious area basis was 5.9 kg m^{-2}, which is approximately 0.7 kg m^{-2} higher than the average C stored in live trees of all forest lands in the state of Georgia (Birdsey, 1992).

Effect of Urban Land-Use Change

The potential for urban areas to sequester or lose SOC is exemplified by our analysis of land-use change effects on C pools for the six cities. For those cities in the northeastern United States (Boston and Syracuse) there was 1.6-fold less SOC post- than in pre-urban development scenarios (Table 7). By contrast, cities located in warmer and or drier climates, such as Chicago and Oakland, had slightly higher (6 and 4%, respectively) SOC

Table 5. Estimated soil organic carbon (SOC) densities by land use and land cover for each region of the United States. Agriculture, forest, grassland, and shrubland SOC density estimates are from Birdsey (1992).

Land use	Region: Southeast†	South Central‡	Northeast§	Mid-Atlantic¶	North Central#	Central††	Rocky Mountain‡‡	Pacific Coast§§
	kg m^{-2}							
Agriculture	2.6	2.4	6.0	4.2	5.3	3.2	2.8	3.7
Commercial–industrial–transportation	3.3¶¶	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Forest	7.7	7.6	16.2	11.6	13.1	8.3	8.0	9.8
Grasslands	3.9	3.4	8.3	6.2	7.5	5.2	3.8	5.7
Impervious	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Other##	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Park	7.1†††	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Residential	14.4‡‡‡	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Shrubland	3.9	3.4	8.3	6.2	7.5	5.2	3.8	5.7
Wetlands	35.0§§§	35.0	35.0	35.0	35.0	35.0	35.0	35.0

† FL, GA, NC, SC, and VA.
‡ AL, AR, LA, MS, OK, TN, and TX.
§ CT, ME, MA, NH, NY, RI, and VT.
¶ DE, KY, MD, NJ, PA, WV, and OH.
# MI, MN, ND, and WI.
†† KS, IL, IN, IA, MI, NE, and SD.
‡‡ AZ, CO, ID, MT, NM, NV, UT, and WY.
§§ CA, OR, and WA.
¶¶ Average of clean fill values from Table 1 (n = 3). This value is also used for other and impervious categories.
Other category includes bare rock/sand/clay; quarries/strip mines/gravel pits; transitional; and orchards/vineyards/other.
††† Average of park use and grass values from Table 1 (n = 2).
‡‡‡ Average of residential grass values from Table 1 (n = 3).
§§§ Roughly half the global estimate for wetland soils (72.3 kg m^{-2}) and lower than the 45 kg m^{-2} estimates for wetland forests in the United States (Trettin and Jurgensen, 2003).

pools in post- than in pre-urban stages. The large dissimilarity between pre- and post-urbanization estimates for Boston and Syracuse are due to the high concentrations of C in the native forest soils of the northeastern United States (Table 7). The differences found between pre- and post-urban development stages may actually be underestimates because wetlands were not included as a cover type in this analysis.

The lower urban SOC densities in regions with native soils of high SOC and higher urban SOC densities for regions with low native SOC found in this analysis is consistent with the urban convergence hypothesis (Pouyat et al., 2003), which predicts that urban land-use change drives ecosystem structure and function (e.g., SOC densities) over time toward a range of similar endpoints regardless of ecosystem life zone starting points. Indeed, there also is evidence for a "convergence" of SOC pools from comparisons of agricultural soils made by Post and Mann (1990). The authors found that the average loss for soils with high initial SOC was about 23%, while soils with low initial SOC actually increased their C storage after converting to cropland.

Effect of Land Use and Land Cover

In our analysis, we accounted for the amount of soil area that is managed as turf grass (park or residential grass) or has been drastically disturbed (fill) since these areas will vary in their aerial coverage by city (Table 3). We also considered regional differences in SOC densities of native soils for remnant cover types that may occur in an urban area. As a result, the total amount of SOC varied considerably among land-use and land-cover types (Table 8). By far the greatest proportion of SOC for all six cities was found in residential areas (65%), followed by commercial–industrial (11%) and forest (5.6%) types (Table 8). If we combine the cover types that primarily represent remnant soils (forest, greenspace, vacant, wildland), the proportion is 9.4%, a surprisingly high percentage given these are urban areas that by definition have relatively high population densities. The high amount of SOC in residential areas is a product of both the amount of land devoted to residential use (Table 3), the relatively low impervious cover found in residential areas, and the relatively high density of C found in residential soil types (Fig. 1).

Table 6. Estimates of pervious and impervious below- and aboveground total C and C density.

City	Total area	Impervious	Belowground: Pervious: Total carbon	Belowground: Pervious: Carbon density	Belowground: Impervious and pervious: Total carbon	Belowground: Impervious and pervious: Carbon density	Aboveground: Carbon	Aboveground: Pervious: Carbon density	Aboveground: Impervious and pervious: Carbon density
	ha	%	Mg	kg m^{-2}	Mg	kg m^{-2}	Mg	kg m^{-2}	kg m^{-2}
Atlanta	34140	39.8	2223000	10.8	2671000	7.8	1220000	5.9	3.6
Baltimore	20916	50.4	975000	9.4	1323000	6.3	527000	4.5	2.5
Boston	14280	53.9	587000	8.9	841000	5.9	290000	4.4	2.0
Chicago	61368	60.0	2154000	8.8	3369000	5.5	855000	3.7	1.4
Oakland	13241	48.0	573000	8.3	783000	5.9	144000	2.1	1.1
Syracuse	6501	46.5	363000	10.4	462000	7.1	157000	4.5	2.4
Totals and averages	150446	51.9	6875000	9.5	9449000	6.3	3193000	4.4	2.1

Table 7. Net change of total soil organic carbon (SOC) and carbon density (CD) by city. Native and Agriculture soil estimates represent an equal amount of area of each city. Current SOC and CD are taken from Table 6.

	Native		Agriculture		Current		Net change	
City	SOC	CD	SOC	CD§	SOC	CD	SOC	CD
	Mg	kg m^{-2}	Mg	kg m^{-2}	Mg	kg m^{-2}	Mg	kg m^{-2}
Atlanta	2642000	7.7†	884000	2.6	3369000	7.8	727000	0.1
Baltimore	2418000	11.6†	872000	4.2	1323000	6.3	−1095000	−5.2
Boston	2315000	16.2†	858000	6.0	841000	5.9	−1474000	−10.3
Chicago	3185000	5.2‡	1945000	3.2	3369000	5.5	184000	0.3
Oakland	753000	5.7‡	485000	3.7	783000	5.9	29000	0.2
Syracuse	1054000	16.2†	391000	6.0	462000	7.1	−592000	−9.1

† SOC for timberland (Birdsey, 1992).
‡ SOC for grassland (Birdsey, 1992).
§ SOC for cropland (Birdsey, 1992).

State and Regional Estimates

Urban carbon densities (kg m^{-2}) varied widely by state for both aboveground and belowground estimates. Aboveground estimates of urban C density varied from a low of 0.3 (WY) to a high of 5.1 (GA) kg m^{-2}, while belowground estimates varied from 4.6 (NV) to 12.7 (NH) kg m^{-2} (Table 9). The ratio of belowground to aboveground estimates of C storage also varied widely, but all states had a ratio above 1.0 (Table 9). Three states had ratios of above 10.0 (NM, RI, WY) and three others were above 5.0 (CA, ND, TX). With the exception of RI, all of these states posses urban areas located in arid climates. Moreover, the high ratios of these states were more a function of having relatively low aboveground C densities (<1.0 kg m^{-2}) than particularly high belowground C densities (Table 9). Therefore, the high ratios may be due to relatively low percentage of tree cover in the urban areas of these states. Moreover, the state aboveground estimates did not include the non-tree biomass (herbaceous cover and woody plants with diameter at breast height < 2.5 cm), which would have contributed to the aboveground carbon estimate and reduced the ratio, especially in arid climates where non-tree biomass may account for a greater proportion of the overall aboveground biomass. The belowground to aboveground ratio of the United States was 2.8 (Table 9), which is slightly higher than the global estimate of 2.7 (Schlesinger and Andrews, 2000). Again, this difference may be a reflection of the relatively low canopy cover in urban areas and relatively high SOC densities found in residential lawns. Whatever the cause, the state and regional analysis suggests that urban soils have the potential to store relatively high amounts of SOC.

Regional estimates of urban SOC densities and total storage reflected the differences in the native SOC pools and the amount of urban area in each region (Table 10). The lowest regional estimates of urban SOC densities were in the Rocky Mountain and South Central regions (5.2 and 6.6 kg m^{-2}, respectively), while the highest estimate (11.0 kg m^{-2}) was calculated for the Northeast. While having highly variable climate and soil types due largely to differences in elevation, the Rocky Mountain and South Central regions are largely arid and thus have soils (including urban remnant soils) inherently low in SOC. By contrast, the Northeast has climate conditions (cooler and wetter than Rocky Mountain and South Central regions) that favor a higher accumulation of C in soil. Regional differences that may occur in SOC pools of urban soils could not be assessed due to a lack of data. Nonetheless, an important factor affecting regional differences of total urban SOC storage is the amount of urban area in each region. The amount of urban area in the South Central region is more than twofold higher than several of the other regions and as a result this region has

Table 8. Soil carbon estimates by land use for pervious and pervious plus impervious for six cities.† Estimates are calculated from Tables 4 and 5.

		Pervious			Pervious and impervious	
Land use	Total area	Area	Total carbon	Carbon density	Total carbon	Carbon density
	ha	ha	kg	kg m^{-2}	kg	kg m^{-2}
Agriculture	259	247	10000	4.0	10000	3.9
Barren	204	203	7000	3.3	7000	3.3
Commercial–industrial	31170	8827	291000	3.3	1029000	3.3
Forest	6172	5961	519000	8.7	525000	8.5
Green space	728	638	103000	16.2	106000	14.6
Institutional—vegetation dominated	5342	2901	206000	7.1	287000	5.4
Institutional—building dominated	2777	1284	42000	3.3	92000	3.3
Institutional	4778	2338	77000	3.3	158000	3.3
Miscellaneous	36	34	1000	3.3	1000	3.3
Park	1856	1721	122000	7.1	127000	6.8
Residential	73327	33568	4824000	14.4	6136000	8.4
Transportation	13041	6274	207000	3.3	430000	3.3
Urban open	5569	4024	239000	5.9	290000	5.2
Vacant	2559	1839	81000	4.4	105000	4.1
Wildland	2628	2549	145000	5.7	148000	5.6
Total	150446	72406	6874000		9451000	

† The six cities are Atlanta, Baltimore, Boston, Chicago, Oakland, and Syracuse.

Table 9. Estimated below- and aboveground carbon storage, including ratio of below-total carbon to above-total carbon, and the portion of state in urban land. Total belowground carbon storage and density were calculated using values from Table 4 and 5.

	Aboveground†			Belowground					
State	Urban area	Carbon storage	Carbon density	Urban area	Carbon storage‡	Carbon density	Total above- and belowground	Below- to aboveground ratio of carbon storage	Urban land
	km^2	Mg	kg m^{-2}	km^2	Mg	kg m^{-2}	Mg		%
AL	8487	37839000	4.5	7637	54798000	7.2	92637000	1.4	6.3
AR	3435	7943000	2.3	3371	22009000	6.5	29952000	2.8	2.5
AZ	9218	9720000	1.1	7980	37635000	4.7	47355000	3.9	3.1
CA	27348	27574000	1.0	22525	149844000	6.7	177418000	5.4	6.4
CO	4345	5225000	1.2	3391	19673000	5.8	24898000	3.8	1.6
CT	4085	8237000	2.0	3313	37529000	11.3	45766000	4.6	28.5
DC				177	1288000	7.3	1288000		
DE	566	2424000	4.3	569	4911000	8.6	7335000	2.0	8.8
FL	18407	31329000	1.7	15628	152471000	9.8	183800000	4.9	10.8
GA	8338	42651000	5.1	8149	65794000	8.1	108445000	1.5	5.4
IA	3148	9638000	3.1	2971	19201000	6.5	28839000	2.0	2.2
ID	966	2287000	2.4	948	4748000	5.0	7035000	2.1	0.4
IL	9165	28570000	3.1	8442	59567000	7.1	88137000	2.1	6.1
IN	5000	14430000	2.9	4790	31327000	6.5	45757000	2.2	5.3
KS	2575	4883000	1.9	2458	16376000	6.7	21259000	3.4	1.2
KY	3374	10424000	3.1	3462	28451000	8.2	38875000	2.7	3.2
LA	5374	12577000	2.3	4543	40929000	9.0	53506000	3.3	4.0
MA	6893	16131000	2.3	5897	69678000	11.8	85809000	4.3	25.1
MD	4525	16784000	3.7	4043	34205000	8.5	50989000	2.0	14.4
ME	2887	12738000	4.4	2614	31973000	12.2	44711000	2.5	3.1
MI	7494	20588000	2.8	7272	63859000	8.8	84447000	3.1	3.0
MN	6775	23438000	3.5	5834	60800000	10.4	84238000	2.6	3.0
MO	5655	16006000	2.8	5144	34918000	6.8	50924000	2.2	3.1
MS	3365	12015000	3.6	3096	26027000	8.4	38042000	2.2	2.7
MT	4365	19946000	4.6	4363	25260000	5.8	45206000	1.3	1.1
NC	6419	25472000	4.0	6306	49561000	7.9	75033000	1.9	4.6
ND	457	330000	0.7	447	3096000	6.9	3426000	9.4	0.2
NE	1061	2071000	2.0	1062	6513000	6.1	8584000	3.1	0.5
NH	1678	7621000	4.5	1673	21292000	12.7	28913000	2.8	6.9
NJ	6916	26485000	3.8	6462	65578000	10.1	92063000	2.5	30.6
NM	2316	1028000	0.4	2228	10785000	4.8	11813000	10.5	0.7
NV	3195	2926000	0.9	2992	13815000	4.6	16741000	4.7	1.1
NY	10127	24636000	2.4	9277	90359000	9.7	114995000	3.7	7.2
OH	9923	35155000	3.5	9414	76416000	8.1	111571000	2.2	8.5
OK	7940	10650000	1.3	6804	34280000	5.0	44930000	3.2	4.4
OR	2280	6411000	2.8	2269	15833000	7.0	22244000	2.5	0.9
PA	8363	26611000	3.2	8405	72295000	8.6	98906000	2.7	7.0
RI	926	762000	0.8	829	9335000	11.3	10097000	12.3	23.2
SC	4380	16125000	3.7	3936	32657000	8.3	48782000	2.0	5.3
SD	617	1096000	1.8	577	3612000	6.3	4708000	3.3	0.3
TN	7382	29976000	4.1	6787	45672000	6.7	75648000	1.5	6.8
TX	26573	25809000	1.0	23894	147455000	6.2	173264000	5.7	3.8
UT	2577	3337000	1.3	2190	11766000	5.4	15103000	3.5	1.2
VA	8869	28960000	3.3	5985	46254000	7.7	75214000	1.6	8.0
VT	416	1385000	3.3	435	4510000	10.4	5895000	3.3	1.7
WA	5679	17650000	3.1	4823	34256000	7.1	51906000	1.9	3.1
WI	4565	10894000	2.4	4390	35369000	8.1	46263000	3.2	2.7
WV	1086	4239000	3.9	1080	9249000	8.6	13488000	2.2	1.7
WY	797	265000	0.3	675	3908000	5.8	4173000	14.7	0.3
Total	280332	703291000		251552	1937139000	7.7	2640430000	2.8	

† Aboveground data are from Nowak and Crane (2002).

‡ Each state was assigned to a region and each regional land use was assigned a carbon density (Table 5). The total belowground carbon storage was calculated by multiplying the impervious land-use area by the impervious soil organic carbon (SOC) density of 3.3 and adding the pervious land-use area multiplied by the appropriate land-use SOC density.

the highest amount of C stored in soil, though the C densities are relatively low (Table 10).

The total weighted average of SOC density for all soils in the conterminous United States was 7.7 kg m^{-2}. Taking into account the standard errors of SOC densities for each of the urban soil types (Fig. 1), the density for all urban areas ranges from 7.5 to 7.9 kg m^{-2}. This range in density is similar to an original estimate of 8.2 kg m^{-2} (Pouyat et al., 2002), even though the original analysis did not account for (i) differences in land cover among urban areas, (ii) differences in SOC densities of regional differences in remnant soils, and (iii) SOC densities of wetlands. Although the allocation of cover type by region allowed for interregional comparisons in the current analysis, by averaging these differences in the previous analysis the two estimates should not vary greatly. However, by varying regional differences in native SOC densities, the new estimate reduced the SOC in the undisturbed soils category of the original calculation (Pouyat et al., 2002). This reduction was most notable in the South Central regional estimate, which had the largest urban area of all the regions, and where the SOC densities of native soils (Table 5, shrub and forest lands at 3.4 and 7.6 kg C m^{-2}, respectively) were lower than the original undisturbed soil estimate (9.4 kg m^{-2}) used for all urban areas (Pouyat et al., 2002).

By contrast, our inclusion of wetland soils increased our estimate relative to the original analysis. With the

Table 10. Estimated urban soil carbon densities and soil organic carbon (SOC) by region. Region estimates calculated from data in Table 9.

Region	Total area	Carbon density	SOC	Urban land
	10^{10} m	kg m^{-2}	10^{14} g	%
Central	2.5	6.7	1.7	2.3
Mid-Atlantic	3.4	8.7	2.9	7.5
North Central	1.8	9.1	1.6	2.2
Northeast	2.4	11.0	2.6	8.2
Pacific Coast	3.0	6.8	2.0	4.1
Rocky Mountain	2.5	5.2	1.3	1.2
South Central	5.6	6.6	3.7	4.1
Southeast	4.0	8.7	3.5	7.1
Total	25.2	7.7	19.4	3.4

current analysis, wetland SOC density was 35 kg m^{-2}, which is roughly 50% lower than the global estimate for wetland soils (72.3 kg m^{-2}), and about 30% lower than other estimates of wetland soils in temperate regions (Trettin and Jurgensen, 2003; Wang and Kanehl, 2003). We lowered the density value for urban wetlands based on predicted effects of urban development on wetland soils (Trettin and Jurgensen, 2003), though more data is needed to make a more accurate estimate. The importance of including wetland soil in our analysis is evident in the disproportionate effect of wetlands on global C pool estimates. For instance on a global scale, the area of wetlands is relatively small to other life zones; however, wetlands at this scale make up the highest proportion of SOC storage due to relatively high SOC densities (Post et al., 1982). Likewise, our state and regional analysis was very sensitive to changes in wetland areas, which comprised 3.6% of urban areas in the conterminous United States. If we increased our estimate of SOC densities for urban wetland soils to represent estimates of the conterminous United States (45.0 kg m^{-2} from Trettin and Jurgensen, 2003) and global scale (72.3 kg m^{-2} from Post et al., 1982) our national estimate of SOC density for urban soils would increase from 7.7 to 8.1 and 9.0 kg m^{-2}, respectively.

CONCLUSIONS

With a limited number of measurements of urban soils available, SOC densities varied widely among different soil and land-use and land-cover types. Soils of residential lawns appear to have the highest density of C in urban landscapes—higher than many forest soils in the conterminous United States. Thus far, the SOC densities measured for residential lawns also appear to be the least variable of the made-soil types included. The relatively high SOC density of residential soils is most likely a result of lawn management, which typically includes supplements of water and nutrients to maximize grass productivity. Moreover, turfgrass ecosystems can accumulate SOC at rates similar to those for grasslands and some forests due to the absence of annual soil disturbances that occur in agricultural systems.

The city analysis showed the importance of accounting for soils beneath impervious surfaces and in remnant patches of native vegetation. Remnants accounted for almost 10% of the area in our city analysis, and, depending on the SOC density of the native soils, could account for up to 34% of the SOC pool of a city. Moreover, when covered soils were excluded from the analysis, the estimated SOC densities rose substantially for each land-use and land-cover type, indicating the potential for urban soils in pervious areas to sequester large amounts of SOC.

The comparison of pre-agricultural, agricultural, and post-urban estimates of SOC pools of each of the six cities showed the potential for large decreases in SOC pools post-urban development for cities located in the Northeast, where native soils have relatively large SOC densities. By contrast, cities located in warmer and or drier climates tended to have slightly more SOC post- than in pre-urban development. These estimates are consistent with an earlier hypothesis that SOC should be less variable among urban landscapes than among native soils on regional and global scales.

Densities by state for both aboveground and belowground estimates also varied widely. Differences in regional SOC densities were based on differences in native soil types (i.e., urban remnant soils) and regional land-use patterns associated with urban areas. Due to a lack of data, we were unable to assess regional differences that may occur in urban SOC pools. The total weighted average of SOC density for all urban soils in the conterminous United States was 7.7 ± 0.2 kg m^{-2}, which was remarkably close to a previous estimate. Thus far the variation around this estimate, as calculated from the variance of SOC densities of individual soil types, resulted in a range of only ±2.6%. However, this estimate is based only on a limited number of studies from temperate regions and is particularly sensitive to estimates of the aerial coverage and SOC density of urban wetland soils. More data is needed from other regions to determine the range in measurement of urban SOC densities. In addition, our assessment of urban land-use conversion on a city basis showed the potential for substantial losses of SOC in temperate regions, while in more arid climates urban conversions have the potential to increase belowground C storage, assuming our urban soil data are representative of urban soils in these regions. In conclusion, urban soils play a significant role in the overall storage of C in urban landscapes due to relatively high belowground to aboveground C ratios and high SOC densities.

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