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Short communication

Depleted soil carbon and nitrogen pools beneath impervious surfaces

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ABSTRACT

Urban soils and vegetation contain large pools of carbon (C) and nitrogen (N) and may sequester these elements at considerable rates; however, there have been no systematic studies of the composition of soils beneath the impervious surfaces that dominate urban areas. This has made it impossible to reliably estimate the net impact of urbanization on terrestrial C and N pools. In this study, we compared open area and impervious-covered soils in New York City and found that the C and N content of the soil (0–15 cm) under impervious surfaces was 66% and 95% lower, respectively. Analysis of extracellular enzyme activities in the soils suggests that recalcitrant compounds dominate the organic matter pool under impervious surfaces. If the differences between impervious-covered and open area soils represent a loss of C and N from urban ecosystems, the magnitude of these losses could offset sequestration in other parts of the urban landscape.

1. Introduction

Urban areas are growing in population (United Nations, 2011), land area (Seto et al., 2011), and ecological significance (Vitousek et al., 1997). The land cover changes that accompany urbanization include increased impervious surface area (ISA) and replacement of natural vegetation with lawns. These changes result in habitat loss and fragmentation (Theobald et al., 1997), and a decline in the environmental services provided by native ecosystems (Vitousek et al., 1997). Yet a growing body of literature suggests that urban soils and vegetation can still provide a number of important ecosystem services, including C and N sequestration (Golubiewski, 2006; Townsend-Small and Czimczik, 2010; Raciti et al., 2011), immobilization of atmospheric N deposition (Raciti et al., 2008), reduction of airborne particulates (Nowak et al., 2006), and stormwater treatment (Dietz and Clausen, 2000; Zhu et al., 2004). But, it is unclear to what extent these ecosystem services, particularly C and N sequestration, are counterbalanced by the associated expansion of impervious surfaces.

Constructed impervious surfaces cover an estimated 580,000 km^2 of the earth's surface, an area larger than Spain (Elvidge et al., 2007). Despite their large area, there have been no systematic measurements of the C and N content or the biological activity of the soils beneath them. Presently, estimates of soil C and N contents in urban ecosystems are based on extrapolation of data from exposed soils, though at least one study has used clean construction fill as a proxy for the unknown composition of the soils beneath impervious surfaces (Pouyat et al., 2006). The paucity of data on the soils beneath impervious surfaces has made it impossible to reliably estimate the net impact of urbanization on terrestrial C and N pools (Pouyat et al., 2003).

The composition and biological activity of impervious-covered soils have remained largely unknown due to their inaccessibility. For this study, we worked with the NYC Department of Parks and Recreation and the Million Trees NYC project (www.milliontreesnyc.org) to collect soil samples from locations where impervious surfaces were being removed for the purposes of tree planting. Our objectives for this work were to 1) systematically measure the C and N content and enzyme activity of impervious-covered soils and 2) to use these data to predict the potential influence of impervious surfaces on terrestrial C and N stocks in urban ecosystems.

2. Methods

We sampled soils under impervious surfaces from 62 newly excavated tree planting sites in the Bronx and Brooklyn, NY. The four neighborhoods we studied (Fig. 1), which have a mixture of medium- to-high density residential, commercial, and some industrial (Hunt's Point only) land use, have been intensively developed for at least a century (NYC Dept of Finance, 2011). An excavator-mounted pneumatic hammer was used to cut the pavement, which was then lifted and removed to reveal the soil underneath (Fig. 2A). Soil cores (5 cm diameter) were collected from the top 0–15 cm, and then from approximately 45–60 cm depth after existing soil in the pit had been excavated for tree planting. Soil cores were taken from near the center of the pavement opening (Fig. 2A), which was typically 1–1.5 m wide and 2–3 m long,

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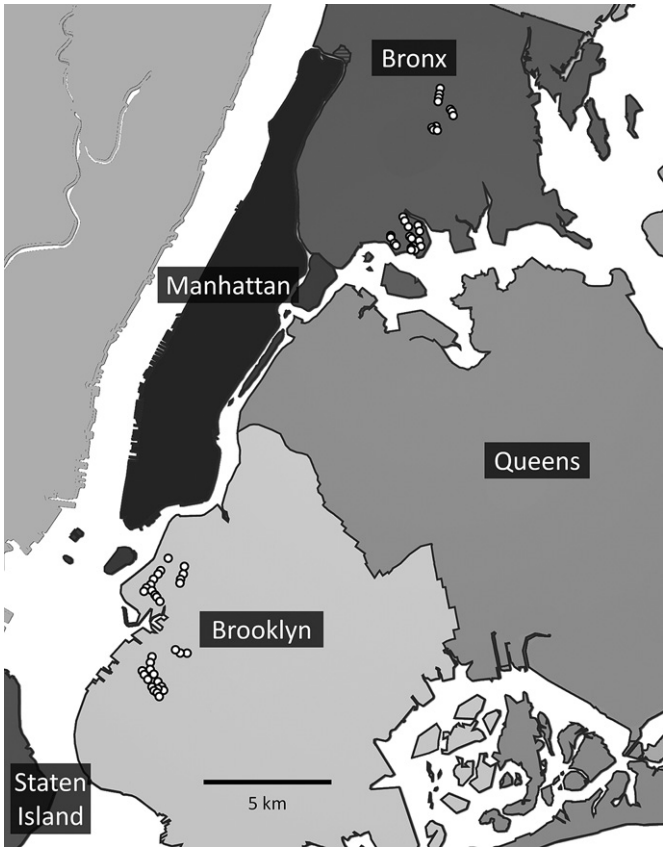

Fig. 1. Map of the study area showing the five boroughs of New York City and the 62 locations (white dots) where impervious covered soils were collected at 0–15 and 45–60 cm depth intervals. Soil samples were clustered in four neighborhoods in the Bronx and Brooklyn (from north to south): Tremont ($n = 11$), Hunt's Point ($n = 18$), Red Hook ($n = 15$), and Sunset Park ($n = 18$).

using a 5 cm diameter AMS slide-hammer corer with a 15 cm long sampler cup (AMS Equipment Corp., American Falls, Idaho). Additional soil cores (0–15 cm and 15–30 cm depth) were collected from proximate open areas that were within the same city block. The open area reference sites consisted of residential and commercial lawns and gardens, grassy medians between the sidewalk and the street, and public greenspaces. Logistical constraints did not allow us to collect deeper soil cores (e.g. 45–60 cm) from open areas.

Immediately upon collection, cores were transferred to coolers with dry ice and transported to the laboratory for processing (2–5 days later). The dry ice was replenished every 48 h to ensure that soil cores remained frozen. All cores were analyzed for total C and N content and enzymatic activity associated with decomposition of cellulose, chitin, and lignin (beta glucosidase [BG], alpha-N-acetylglucosaminidase [NAG], and peroxidase [PEROX], respectively) and were processed as described below.

Intact soil cores were first weighed and then sieved to remove rocks, coarse roots, and organic material greater than 2 mm in size. Approximately 20 g of the sieved, homogenized soil was transferred to 20 ml nalgene bottles and moved to a −80 °C freezer for storage prior to extracellular enzyme analysis. Of the remaining homogenized soil, 50 g were finely ground and a 20 mg subsample of this well-mixed material was loaded into a 9 × 5 mm tin capsule. This encapsulated subsample was analyzed for total carbon (C) and nitrogen (N) content by flash-combustion/oxidation using a Thermo Finnigan Flash EA 1112 elemental analyzer (0.06% C and 0.01% N detection limits). In addition, we analyzed a subset of soil samples ($n = 36$) for organic C via the loss on ignition method (10 g soil for 8 h at 400 °C (Nelson and Sommers, 1996)). The remaining, frozen soil samples were assayed for the activity of extracellular enzymes involved in the decomposition of cellulose, chitin, and lignin (BG, NAG, and PEROX, respectively, [see (Finzi et al., 2006)]). The BG and NAG enzyme assays were analyzed fluorimetrically using a microplate fluorometer with 365 nm excitation and 450 nm emission filters. Peroxidase activities were measured spectrophotometrically by measuring absorbance at 450 nm using a microplate spectrophotometer. Statistical analysis was carried out using the R 2.11.0 open source software. Parenthetically reported errors are standard errors; data distributions were largely non-homoscedastic.

3. Results and discussion

Soil C densities in the upper 15 cm were 66% (±11.6% SE, $p < 0.001$) lower beneath impervious surfaces than they were in open areas (2.29 versus 5.67 kg C/m^2, respectively, Fig. 2B). The soil C densities observed at the open sites are comparable to suburban and rural forests measured outside of NYC (e.g. Pouyat et al., 2002). Carbon densities decreased with depth for both impervious

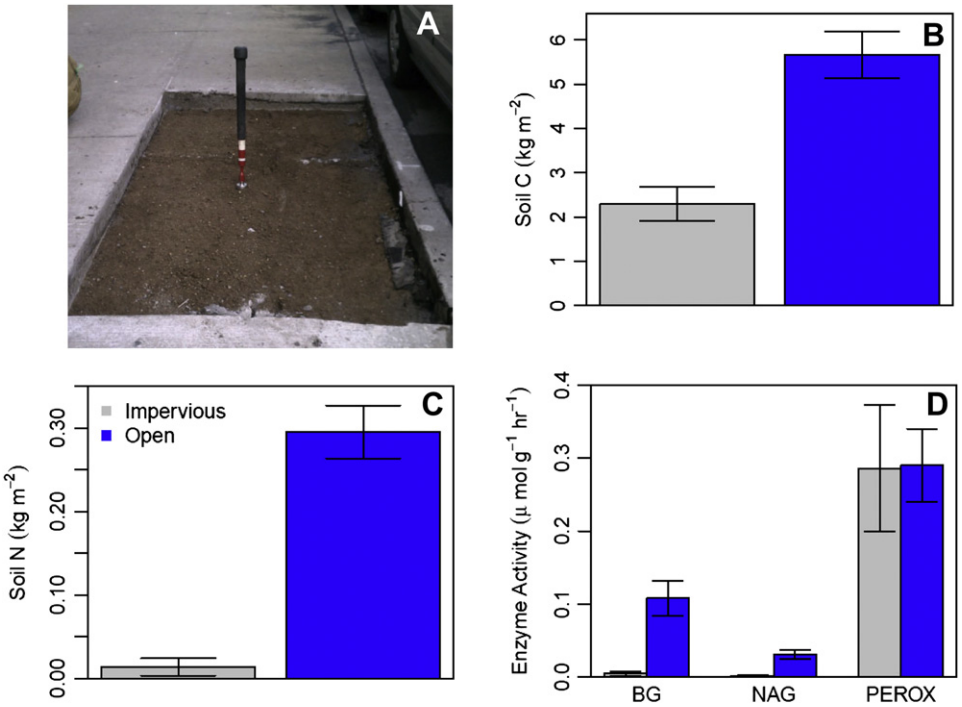

Fig. 2. Composition and enzyme activity of open and impervious-covered soils at 0–15 cm depth (mean ± SE). (A) Example of impervious surface removal for tree planting for the Million Trees NYC project. Concentration (kg m^{-2}) of carbon (B) and nitrogen (C). (D) Beta glucosidase [BG], alpha-N-acetylglucosaminidase [NAG], and peroxidase [PEROX] enzyme activity.

(0.61 kg C/m^2, 45–60 cm) and open areas (3.97 kg C/m^2, 15–30 cm). There were no statistically significant differences in soil C (open or impervious) between the four neighborhoods (Fig. 1) where soils were sampled. Our results suggest that previous proxies for soil characteristics beneath impervious surfaces, based on clean construction fill (Pouyat et al., 2006), may underestimate C in these soils. Pouyat et al. (2006) observed C concentrations of 3.3 ± 0.93 kg C/m^2 for clean fill at 0–100 cm depth. If the soil C data from this study is normalized to 100 cm depth, we find that these soils may contain ~5.8 kg C/m^2 (assuming that soils between 15 and 100 cm contain 0.61 kg C/m^2). The precise mechanisms of C loss from these soils are unknown, but likely possibilities include loss to the atmosphere as CO_2 via decomposition; aqueous losses as dissolved organic and inorganic C; or physical removal of topsoil during the construction process.

Nitrogen densities in the top 15 cm were 95% lower (±11.3%, $p < 0.001$) in the soils under impervious surfaces than in open area soils (0.014 versus 0.30 kg N/m^2, Fig. 2C) and typically less than 0.1% by mass (Fig. 3A). At 45–60 cm depth, N densities were generally near or below the detection limit of our instrument (0.01% N). We could find no published studies that have either quantified soil N, or used a proxy, to estimate the N composition of impervious-covered soils in urban ecosystems. As with C, the loss pathways for N are unknown, but may include aqueous losses as dissolved organic and inorganic N, gaseous losses resulting from denitrification, or physical removal of topsoil at the time of development.

In most soils, there is a tight coupling between stocks and fluxes of C and N, reflecting the origin and metabolism of the source material. Plant leaves and roots typically contain C and N in a ratio of ~45:1 (McGroddy et al., 2004) reflecting the mix of structural and biochemical machinery required for leaf display, photosynthesis, and nutrient acquisition. Once shed, soil microorganisms decompose these tissues leaving their imprint on the stoichiometry of C and N in the soil, typically ranging between 5 and 30:1 (Cleveland and Liptzin, 2007). The mean C to N ratio observed in open area soils was 19:1, which is within the range of natural variation for soils in the region. The soils beneath impervious surfaces contained surprisingly high ratios of C to N with a mean of 164:1. Regressions of the concentration of C as a function of N in the open area soils revealed a strong linear relationship between the two variables at the 0–15 and 15–30 cm depth intervals ($R^2 = 0.73$ and $R^2 = 0.60$, respectively; Fig. 3). There was no discernable relationship for the soils beneath the impervious surfaces, which combined with extraordinarily high C to N ratios suggests that paving decouples the cycles of C and N in soil.

The activity of extracellular enzymes suggests near starvation of microbial communities beneath impervious surfaces, consistent with the decoupling of the soil C and N cycles. The activities of the enzymes that decompose labile, energy- and N-rich organic matter (BG and NAG) were near zero in the soils beneath impervious surfaces, whereas their activity was maintained in open soils (Fig. 2D). The only measureable activity was that of PEROX, an enzyme that attacks the lowest energy- and nutrient-yielding substrates. Our analysis from a subsample of soil cores ($n = 36$) revealed a non-significant mean difference between total and organic C concentrations (-0.04 ± 0.26, $p = 0.87$), though the loss on ignition method can overestimate organic C in some clay-rich soils. This result does not preclude the presence of black carbon, which can be a significant component of some urban soils (e.g. He and Zhang, 2009), but it suggests that BC and other inorganic C would be a small fraction of the total C pool.

The sampling for this study was opportunistic, based on urban tree planting locations. However, the consistency of the results across sites suggests widespread loss or construction-related removal of C and N from beneath impervious surfaces. Setting aside physical removal, the organic content of a soil is governed by the balance of inputs (e.g. plant litter) and outputs (e.g. decomposition). We would expect organic matter inputs to be dramatically reduced beneath impervious surfaces. However, it is unclear if decomposition or dissolved losses would also be reduced. Impervious surfaces are not truly impervious to air or water as evidenced by the lack of redoximorphic features in the soils we surveyed and high soil moisture contents that were comparable to open area soils at the time of collection (24.6 ± 2.2 and 28.8 ± 1.6% volumetric water content for open and impervious soils, 0–15 cm depth, respectively).

We cannot be certain that C and N were truly 'lost' (e.g. to the atmosphere via decomposition), but if they were, this would represent a considerable alteration of the terrestrial nutrient and energy balance of urban ecosystems. If we assume that the patterns of *potential loss* inferred by this study hold true for other impervious-covered soils, and that the mean global soil C concentration is 9.9 kg C/m^2 with a C:N ratio of 15:1 (Schlesinger, 1997), this would suggest potential organic matter losses on the order of 3.2 Pg C and 0.36 Pg N from the soils under the world's 580,000 km^2 of impervious surface area (Elvidge et al., 2007). For the United States, the potential loss of ~0.6 Pg C and ~0.07 Pg N associated with 113,000 km^2 of impervious surface (Elvidge et al., 2004) would be sufficient to offset the ~0.4 Pg C and ~0.04 Pg N storage potential of lawn soils [based on 165,000 km^2 of lawn area (Milesi et al., 2005) and estimated C and N accumulation rates of 0.082 kg C m^{-2} yr^{-1} and 0.008 kg N m^{-2} yr^{-1} (Raciti et al., 2011) for the first 30 years after lawn establishment (Qian and Follett, 2002)]. These potential soil C losses would be comparable in magnitude to

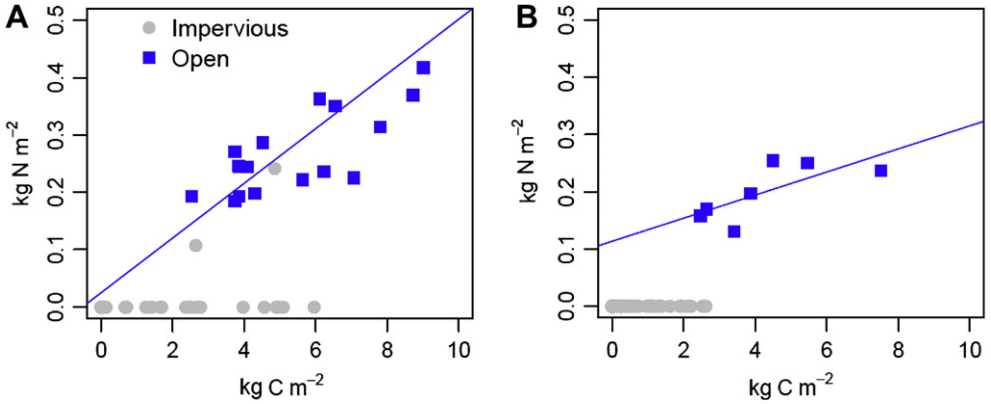

Fig. 3. Carbon vs. nitrogen concentration for open and impervious-covered soils (mean ± SE). Carbon vs. nitrogen at 0–15 cm (A), and 15–30 cm (open) and 45–60 cm (impervious-covered) (B).

the C stored in urban trees in the coterminous United States (Nowak and Crane, 2001), and do not include the large vegetative C losses associated with initial land use change to urban (Imhoff et al., 2004; Hutyra et al., 2011).

4. Conclusions

Our data suggest a potentially large and previously unmeasured source of organic matter loss or removal from areas that are now covered by impervious surfaces, but more data are needed to determine the fate of this material. The ages of the sites in this study make it difficult to determine whether topsoil was removed during the development process or whether C and N was lost or gained by these soils since the time of development. The fate of the 'missing' C and N beneath impervious surfaces is of considerable importance because aqueous losses of NO_3^- could impair water quality and coastal ocean productivity, while gaseous losses of CO_2 and N_2O would contribute to climate change. Future studies that examine a chronosequence of sites might reveal greater mechanistic insights about C and N transformations beneath impervious surfaces. Urban areas are expected to account for all population growth over the next half-century (United Nations, 2011). If science is to inform development policies that minimize environmental degradation and enhance urban ecosystem services, then a better understanding of the biogeochemical consequences of urban soil disturbance is of critical importance.

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