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Influence of urban land development and soil rehabilitation on soil–atmosphere greenhouse gas fluxes

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ABSTRACT

Urban landscapes often have altered soil–atmosphere fluxes of major greenhouse gases (GHGs) including carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) when compared to their rural counterparts. It is unclear to what degree soil disturbance during urbanization contributes to these altered emissions. In addition, rehabilitation of degraded urban soils through deep tillage and organic amendment may improve the soil's ability to support vegetation, but its effect on subsequent soil GHG emissions is unknown. In 2007, twenty-four plots were either left undisturbed or subjected to topsoil stripping, grading and compacting to mimic typical land development followed by one of three treatments: 10 cm topsoil replaced (typical practice); typical practice plus tilling; or compost incorporation to 60-cm depth, followed by typical practice plus tilling (rehabilitation). Soil–atmosphere CO_2, N_2O, and CH_4 fluxes were measured seasonally from fall 2011 to summer 2013. Typical land development practices did not increase global warming potential (GWP) when compared to undeveloped land. Post-development soil rehabilitation, however, resulted in greater GWP (CO_2eq ranging from 0.7 to 12.1 g C m^{-2} d^{-1}) than both undisturbed soils and those subjected to typical development practices (CO_2eq ranging from 0.1 to 5.6 g C m^{-2} d^{-1}) driven primarily by increased CO_2 efflux (ranging from 0.8 to 12.0 g C m^{-2} d^{-1} compared to 0.2 to 5.5 g C m^{-2} d^{-1} in other treatments). All soils were CH_4 sinks (ranging from −0.8 to −0.2 mg C m^{-2} d^{-1}) but CH_4 consumption was too variable to demonstrate treatment effects. Likewise, N_2O fluxes were largely consistent across treatments. Although greater GHG emissions in rehabilitated soil may be offset by increased plant biomass production, our study only assessed soil–atmosphere fluxes. Results suggest that soil disturbance history and management should be considered when assessing the impact of urban land development on GHG emissions.

1. Introduction

Over the last three decades, global greenhouse gas (GHG) emissions have increased by an average of 1.6% per year (IPCC, 2007). Global carbon dioxide (CO_2) emissions, the largest overall contributor to global warming, increased by 3.4 Pg C y^{-1} from 1990 to 2011 with average annual growth rates of 1.9% in the 1980s, 1.0% in the 1990s, and 3.1% since 2000 (Peters et al., 2012). Along with CO_2, nitrous oxide (N_2O) and methane (CH_4) are major GHGs projected to increase by 157–227% and 137–151%, respectively, by the end of this century (Tian et al., 2012). As a result, by 2030, GHG emissions are projected to have increased by 25–90% compared to 2000 (IPCC, 2007). The continuing rapid increase in GHG emissions offers a compelling reason to pursue climate change mitigation by offsetting GHG emissions across a broad range of human activities. Urban areas, where 70% of the world's population is expected to live by 2050 (Seto and Shepherd, 2009), are significant contributors to global GHG emissions and average annual urban per capita GHG emissions can reach more than 15 tons CO_2 equivalent (CO_2eq) (Hoornweg et al., 2011). Although the bulk of these emissions results from energy use, land use change and urbanization are also critical factors at the regional and local scales (Karl and Trenberth, 2003). A significant element of land use change is the soil disruption that typically accompanies urban land development, including topsoil removal and replacement, grading, compaction, and construction. Soil movement and post-development soil treatment can have profound effects upon soil carbon (C) stores (Chen et al., 2013) and may be an underlying driver of these altered GHG emissions. However, a better understanding of the role of land development in altered GHG emissions and the consequent opportunities for mitigation by post-development soil treatments would better inform GHG mitigation strategies related to soil management during land development (e.g., protection of soils during development).

Abbreviations: TP, typical urban land development practice; ET, enhanced topsoil; PR, profile rebuilding; UN, undisturbed soil; GWP, global warming potential.

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North America is a net atmospheric CO_2 source even though net primary production offsets about 35% of the fossil-fuel-based CO_2 emissions by transferring atmospheric C to vegetation, soils, and wood products (King et al., 2012). Some of the higher emissions in urban areas are due to soils. For example, in Phoenix, Arizona, the atmospheric CO_2 levels in the metropolitan region were 50% greater than the surrounding non-urban areas; 80% was from anthropogenic sources while 16% was from soils (Koerner and Klopatek, 2002). Although soil CO_2 emissions will vary significantly by region, it is still unclear whether urban soils are a net CO_2 source or sink and whether this is primarily influenced by management inputs or the initial process of urbanization. While CO_2 fluxes from soils in Phoenix, Arizona were lower in urban sites compared to rural sites along an urban–rural gradient in a desert landscape (Koerner and Klopatek, 2010), in Fort Collins, Colorado, CO_2 emission from urban lawns was more than five times that from native grasslands likely due to irrigation and N inputs (Kaye et al., 2005). In Chicago, Grimmond et al. (2002) found that the atmospheric CO_2 concentration was elevated in the city even though negative land–atmosphere CO_2 fluxes occurred in daylight during the growing season over a suburban forested measurement site, indicating the significant effect of urban vegetation on GHG emission and C sequestration through photosynthesis. Urban vegetative biomass both influences and is influenced by soil properties. For example, vegetation affects below-ground root turnover (Jha and Mohapatra, 2010; Nowak and Crane, 2002) and thus soil C stores. Thus the role of soils in CO_2 emissions is complex.

Nitrous oxide is a more powerful GHG than CO_2 (with a global warming potential 298 times that of CO_2 over a 100-year horizon), although it is a much smaller contributor to global warming (Dalal et al., 2003). Previous studies have documented that urbanization increases N_2O emissions compared to natural lands. For example, urban lawns in both Fort Collins, Colorado and Phoenix, Arizona had higher N_2O emissions than their nonurban counterparts (Hall et al., 2008; Kaye et al., 2004). Although, like CO_2 emissions, this effect varies with region and management practices. For example, in southern California, urban landscape N_2O emissions were approximately equal to or only slightly greater than agricultural emissions (Townsend-Small et al., 2011). Fertilizer application, soil moisture, soil temperature, disturbance frequency, and soil amendments have been reported as factors associated with increased urban soil N_2O emissions (Bijoor et al., 2008; Groffman et al., 2009; Huang et al., 2004; Maggiotto et al., 2000).

Methane, also a powerful GHG (with a global warming potential 25 times that of CO_2 over a 100-year horizon), is produced in anaerobic soil environments. As a whole, soils are a CH_4 sink, taking up 22 ± 12 Tg CH_4 from the atmosphere annually and playing a significant role in the global atmospheric CH_4 budget (Dutaur and Verchot, 2007). Methane uptake capacity varies by land use, climate, latitude, rainfall, temperature, and soil texture (Dutaur and Verchot, 2007; Goldman et al., 1995; Kaye et al., 2004). Temperate forests with coarse soil texture, for example, tend to have high CH_4 consumption (Dutaur and Verchot, 2007). Atmospheric CH_4 consumption by soil is especially sensitive to anthropogenic disturbances, which typically decrease methane consumption (King, 1997) presumably because they create environmental conditions unfavorable for methanotrophic bacteria or restrict diffusion and thus supply of CH_4 to methanotrophs. Urban lawns in Fort Collins, Colorado had about half the CH_4 uptake of nearby natural grasslands (Kaye et al., 2004) while in Baltimore, Maryland, CH_4 uptake capacity was almost completely eliminated in urban lawns (Groffman and Pouyat, 2009). Goldman et al. (1995) observed lower CH_4 consumption rates in urban forests than in rural forests along an urban to rural land-use gradient. However, the sources of these urban–rural disparities have not always been clear. Costa and Groffman (2013) recently revisited their Baltimore study sites and demonstrated that although inorganic N inputs had no immediate effect on CH_4 uptake, these inputs might indirectly influence microbial communities over time resulting in CH_4 uptake reductions in urban sites.

This emissions' variability is likely related to regional ecosystem characteristics as well as the wide variety of land management practices found in urban areas. Although GHG flux differences between urban and nonurban systems and their associated inputs (fertilizer, irrigation, etc.) have been examined, few studies have explored the direct effects of land development or whether GHG emissions can be mitigated via soil remediation practices post development. Some techniques for mitigating GHG emissions through soil management, such as biochar application, have been proposed (as reviewed in Post et al., 2012) and some authors have suggested that urban soils could potentially sequester large amounts of soil organic C, reducing GHG emissions (Lal, 2003; Lorenz and Lal, 2009; Pouyat et al., 2006). In our study, we address whether typical urban land development practices including clearing, topsoil removal, surface grading, and compaction influence GHG emission and whether rehabilitating degraded urban soils via soil profile rebuilding (PR), a rehabilitation technique that uses deep tillage and compost amendment to alleviate the subsurface soil compaction, can help mitigate any increased emissions. Previous work with PR indicates that post-development rehabilitated soils can result in soil C stores and tree growth rates similar to those found on pre-development soil and significantly greater than those found on non-rehabilitated soils (Chen et al., 2013; Layman, 2010). However, the effect of urban land development with or without post-development rehabilitation on soil GHG emissions is not known. Urbanization can result in disruptions to soil aggregates and restrictions to permeability (Gregory et al., 2006; Jim, 1998), which could increase CO_2 emissions as aggregate-protected carbon pools are exposed to microorganisms and reduce CH_4 uptake because of increased soil water content. Soil rehabilitation, however, includes compost additions and loosens compacted soils, potentially increasing root and microbial activity and improving drainage, leading to increased CO_2 emissions but also increased CH_4 uptake. We hypothesized that urban land development would affect GHG emissions even when subsequent vegetation management practices are constant while subsequent soil rehabilitation addressing subsoil compaction will result in emissions similar to undisturbed land. Consequently our study objectives were to: (1) compare GHG fluxes of soils subjected to typical urban land development practices with undisturbed soils; and (2) assess the effect of post-development soil rehabilitation on soil–atmosphere flux of GHGs.

2. Materials and methods

2.1. Site information

The study site, in Montgomery County, Virginia (N 37.200267, W 80.586493), was previously under pasture land use and contains two closely related loamy soils: Shottower loam (fine, kaolinitic, mesic Typic Paleudults) and Slabtown loam (fine-loamy, mixed, mesic Aquic Paleudalfs). Before treatment installation, plots were mowed and existing vegetation was killed via application of glyphosate in the form of Roundup (Monsanto Corp., St. Louis, Missouri). Between May and November 2007, 24 (6 replications × 4 soil treatments) 4.6 × 18.3 m plots were installed in a completely randomized experimental design. Treatments included an undisturbed control, typical urban land development practice, and two types of post-development soil management. With the exception of the control, all plots were subjected to pre-treatments that replicated the scraping and compaction typical of land development: the A horizon was removed by scraping with a front-end loader and stockpiled adjacent to the study site, and the exposed subsoil surface was compacted via 8 passes of a 4808 kg ride-on sheep's foot vibrating compactor (Model SD45D, Ingersoll Rand) to an average bulk density of 1.98 g cm^{-3} at 5–10 cm soil depth. In