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Soil organic carbon distribution in roadside soils of Singapore

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HIGHLIGHTS

- SOC densities (1.1–42.5 kg m^{-2}) of Singapore's roadside soils are high and variable.
- SOC was not related to aboveground vegetation or soil microbial biomass.
- Land-use patterns best explained variance in SOC of Singapore's roadside soils.
- SOC in Singapore's roadside soils appears to be inversely related to urbanization.

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ABSTRACT

Soil is the largest pool of organic carbon in terrestrial systems and plays a key role in carbon cycle. Global population living in urban areas are increasing substantially; however, the effects of urbanization on soil carbon storage and distribution are largely unknown. Here, we characterized the soil organic carbon (SOC) in roadside soils across the city-state of Singapore. We tested three hypotheses that SOC contents (concentration and density) in Singapore would be positively related to aboveground tree biomass, soil microbial biomass and land-use patterns. Overall mean SOC concentrations and densities (0–100 cm) of Singapore's roadside soils were 29 g kg^{-1} (4–106 g kg^{-1}) and 11 kg m^{-2} (1.1–42.5 kg m^{-2}) with median values of 26 g kg^{-1} and 10 kg m^{-2}, respectively. There was significantly higher concentration of organic carbon (10.3 g kg^{-1}) in the top 0–30 cm soil depth compared to the deeper (30–50 cm, and 50–100 cm) soil depths. Singapore's roadside soils represent 4% of Singapore's land, but store 2.9 million Mg C (estimated range of 0.3–11 million Mg C). This amount of SOC is equivalent to 25% of annual anthropogenic C emissions in Singapore. Soil organic C contents in Singapore's soils were not related to aboveground vegetation or soil microbial biomass, whereas land-use patterns to best explain variance in SOC in Singapore's roadside soils. We found SOC in Singapore's roadside soils to be inversely related to urbanization. We conclude that high SOC in Singapore roadside soils are probably due to management, such as specifications of high quality top-soil, high use of irrigation and fertilization and also due to an optimal climate promoting rapid growth and biological activity.

1. Introduction

Soils are the third largest sink of carbon (C), after oceans and geologic sinks and contain almost three-quarters of organic carbon stocks in all Earth's biomes (Edmondson et al., 2014). The amount of C stored in soil is estimated to be 2–4 times more than that stored in the atmosphere and nearly four times the C stored in aboveground biomass (Lal, 2004). Combined these factors give soils the potential to significantly impact the sequestration of atmospheric carbon dioxide (CO_2). Concerns over atmospheric C loading due to increased anthropogenic activities has renewed interest in utilising soils as a receptacle for long-term C storage, particularly in an attempt to offset C emissions associated with global consumption of fossil fuels (DeLuca and Boisvenue, 2012). A slight change in the size of soil organic carbon (SOC) reservoir can potentially alter the atmospheric CO_2 concentration and, ultimately the global climate (Yanli et al., 2010). Therefore assessment of ecosystem C stocks are crucial to understand anthropogenic changes to the

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global C cycle (Jobbagy and Jackson, 2000; Guo and Gifford, 2002; Bradley et al., 2005).

Soils of urban areas represent a wide spectrum in terms of composition and degree of development. Urban soils are playing an increasingly important role in the global carbon cycle. Especially as with the percentage of the global population living in urban areas is increasing drastically, passing from 3.3 billion in 2007 to 6.4 billion in 2050 (United Nations, 2008). In the face of this accelerated urbanization, environmental pressures and impacts on soils will increase and changes in land-use systems potentially cause C losses from terrestrial biosphere including SOC (Xiong et al., 2014). Therefore urban SOC contents vary widely due to human interferences and other urban local environmental factors, such as differences in temperature and rainfall (Pouyat et al., 2003). Research showed wide variability in SOC content within individual cities world-wide range from 0.9 to 43 kg m^{-2} (Table 1). Moreover, urban SOC estimates vary with depth and tend to increase in magnitude and variability as the depth of investigation increases. For example, Pouyat et al. (2002) found SOC to vary from 2.9 to 28.5 kg m^{-2} for the 0–100 cm depths in New York across different land-uses, while Raciti et al. (2012b) found SOC in the 0–15 cm depth beneath impervious surfaces to vary from 5.1 to 6.2 kg m^{-2} in that same city.

Research in urban soils is growing, but the knowledge base of these soils is still quite limited. This paucity of data obscures baseline SOC levels in urban areas, inhibiting the prediction or assessment of the effects of urbanization and land-use change on SOC in cities in various parts of the world. There is an obvious and growing need to understand the constituent of soil organic material and density, content and distribution of SOC in urban soils (Richard et al., 2006; Rawlins et al., 2007; Edmondson et al., 2014). To date, the vast majority of soil C research has been concentrated in non-urban areas. However, research has shown that urban SOC stocks are substantial; for instance, Vasenev et al. (2013) reported significantly higher SOC stock in urban areas compared to non-urban areas in Moscow region. Cities are hotspots for ecological change and we need more information on key ecosystem processes like SOC storage in urban areas (Grimm et al., 2008).

Singapore has been highly recognized for its successful environmental management (Savage and Kong, 1993) despite rapid urbanization and limited land resources. The city-state has also attempted to limit its C emissions and reduce per capita C intensity; it has employed strategies to use urban vegetation as a means of reducing atmospheric C through increase in soil C sequestration. However, urban soil C data are scanty for major regions and countries in South-East Asia including Singapore (Lorenz and Lal, 2015). Urban environmental studies projects developed in Singapore focuses on the above-ground aspects of C sequestration; importance of soil as an effective C sink in urban systems is not yet fully recognized. This study was the first attempt to assess the distribution (both horizontal and vertical) of SOC stock for roadside soils of Singapore. Among the major land-uses in Singapore, street tree landscape in roadside areas comprises 13.5% of all managed vegetation and 3.7% of total land area (LTA, 2013; Tan et al., 2013).

The goal of this research was to analyze the content (concentration and density), and distribution of SOC of the roadside soils in order to investigate predictive factors for explaining soil C stocks in Singapore. Towards this goal, we tested three specific hypotheses: (1) SOC contents (0–100 cm) in Singapore roadside soils would be positively related to aboveground tree biomass; (2) SOC contents (0–100 cm) in Singapore roadside soils would be positively related to soil microbial biomass; and, (3) SOC contents (0–100 cm) would vary regionally and this variance would be explained by land-use patterns.

2. Materials and methods

2.1. Study area

Singapore is a city-state tropical country at the southern tip of Peninsular Malaysia, located between latitude 1°09′N and longitude 103°38′E with a hot and humid climate. Average annual temperature and rainfall throughout the city vary between 24 and 31 °C and 234 cm respectively. The geology of Singapore consists of four major formations: igneous rocks consisting of the ‘Bukit Timah’ granite and the ‘Gombak’ norite, occupying the north and central-north region, sedimentary rocks of the ‘Jurong’ formation, occupying the west and southwest region, quaternary deposit of the Old Alluvium in the eastern region and recent alluvial deposits of the ‘Kallang’ formation (Public Works Department, 1976; Leong et al., 2002), as shown in Fig. 1.

The research concentrated on roadside soils and the soil samples were collected along the streetscape. A key element of Singapore's ‘garden city’ vision is roadside greenery, where an estimated 300,000 street trees are relatively evenly distributed throughout the island (NParks, 2014). In total, Singapore maintains over 3400 linear kilometers of roadway, and the adjacent street tree landscape comprises 13.5% of all managed vegetation, representing 3.7% of Singapore's 716.5 km^2 total land area (Tan et al., 2013).

The average daily traffic volume was 300,400 in 2015 compared to 244,000 in 2004 (LTA, 2014). Road construction guidelines prescribe tree planting strips that are physically isolated from underground utilities or infrastructure, with a rooting space of at least 2 m wide and 1 m deep (LTA, 2014). Since 2009, approved soil mix

Table 1
Comparison of SOC density (kg m^{-2}) for worldwide urban soils.

City	Depth (cm)	SOC content (kg m^{-2})	Reference
Boston, USA	0–10	3.4–4.2	Raciti et al., 2012a
New York, USA	0–15	5.1–6.2	Raciti et al., 2012b
Leicester, England	0–21	1.2–8.6	Edmondson et al., 2014
Fort Collins, USA	0–30	0.2–0.5	Kaye et al., 2005
Stuttgart, Germany	0–30	3–23	Lorenz and Kandeler, 2005
Auburn, USA	0–50	0.7–3.3	Huyler et al., 2014
Chicago, USA	0–60	43	Jo and McPherson, 1995
Chucheon, Korea	30–60	0.9	Jo, 2002
New York, USA	0–100	2.9–28.5	Pouyat et al., 2002
Washington, DC USA	0–100	1.5	Short et al., 1986
Hong Kong	0–100	4.2	Jim, 1998
Baltimore, USA	0–100	3–14	Pouyat et al., 2006
Baltimore, USA	0–100	2–15	Raciti et al., 2011
Moscow, Russia	0–100	14.6	Stroganova et al., 1998
Chicago, USA	0–100	16.3	Jo and McPherson, 1995