# Changes in soil carbon sequestration in *Pinus massoniana* forests along an urban-to-rural gradient of southern China

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**Abstract**

Urbanization is accelerating globally, causing a variety of environmental changes such as increases in air temperature, precipitation, atmospheric $CO_2$, and nitrogen (N) deposition. However, effects of these changes on forest soil carbon (C) sequestration remain largely unclear. Here, we used urban-to-rural environmental gradients in Guangdong Province, southern China, to address the potential effects of these environmental changes on soil C sequestration in *Pinus massoniana* forests. In contrast with our expectations and earlier observations, soil C content in urban sites was significantly lower than those in suburban and rural sites. Lower soil C pools in urban sites were correlated with a significant decrease in fine root biomass and a potential increase in soil organic C decomposition. Variation of soil C pools was also a function of change in soil C fractions. Heavy fraction C content in urban sites was significantly lower than those in suburban and rural sites. By contrast, light fraction C content did not vary significantly along the urban-to-rural gradient. Our results suggest that urbanization-induced environmental changes may have negative effect on forest soil C in the studied region.

## 1 Introduction

Urbanization is accelerating globally, with 50% of the world's population currently living in cities, with projected increases to 70% by 2050 (UNFPA, 2007). Rapid urban development has the potential to alter regional C budgets through urbanization-induced environmental changes (Trusilova and Churkina, 2008; Pouyat et al., 2002). Urbanization-induced environmental changes includes a variety of environmental changing factors caused by accelerating urbanization, such as increases in air temperature, precipitation, atmospheric $CO_2$, and nitrogen (N) deposition (Shen et al., 2008). Numerous studies have shown air temperature (Jones et al., 1990), precipitation (Botkin and Beveridge, 1997; Gilbert et al., 1989), atmosphere $CO_2$ (Idso et al., 2002; Pataki et al., 2003), and N deposition (Lovett et al., 2000; Fenn et al., 2003) to be higher in urban areas than in rural surroundings. This environmental gradient may even be a useful tool for investigating how global environmental change influences forest ecosystem structure and function, since such changes in cities are also known to be major drivers of global change (Carreiro and Tripler, 2005; Shen et al., 2008;).

The current scientific evidence supports that urbanization-induced environmental changes should increase soil C sequestration of urban forests. Results from long-term N addition experiments in the United States and Europe have shown that N deposition can increase forest soil C sequestration of 0.51 to 0.69 Mg C $ha^{-1}$ $yr^{-1}$ (Hyvonen et al., 2008; Pregitzer, et al., 2008). Using a meta-analysis of experiments carried out over >2 yr periods, Jastrow et al. (2005) reported that elevated $CO_2$ concentration would increase soil C sequestration of 0.19 Mg C $ha^{-1}$ $yr^{-1}$. If combined with N addition, this positive effect of elevated $CO_2$ on soil C storage would be more pronounced (van Groenigen et al., 2006; Hungate et al., 2009). This belief was also supported by recent direct field measurements along an urban-to-rural gradient in New York red oak (*Quercus rubra* L.) forests (Pouyat et al., 2002) and in a semi-arid tropical desert ecosystem in Phoenix, Arizona (Koerner et al., 2010). However, besides the above mentioned two direct measurements, this belief has not been tested in other cities, forests and (or) climate zone (Pouyat et al., 2003; Yesilonis and Pouyat 2012). Soil warming induced by elevated urban air temperate may reduce soil C storage in the short-term by increasing decomposition, this may be offset by increasing C input and SOM stabilization in the long-term (Conant et al., 2008; Giardina et al., 2000). As a result, diversity in the responses of forest soil C to urbanization-induced environmental changes may also be existent.

China has undergone rapid urbanization, largely resulting from economic reform and the "open door policy" initiated in late 1978 (Chen et al., 2006). The population of Guangdong Province, southern China, increased nearly two-fold from 1982 to 2010 (i.e., 53.6 million to 104.3 million persons) (SBGP, 2011). Despite this notable increase, no data are available that relate the response of forest soil C to these urbanization-induced changes.

To address this, we established urban-to-rural gradients in Guangdong Province, beginning with the Pearl River Delta (PRD) economic region at the center of development; the PRD covers nearly 25% of the provincial area and supports ~54% of the population (SBGP, 2011). The purpose of this study was to assess the potential effects of urbanization changes on forest soil C in southern China utilizing this urban-to-rural gradient. Masson pine (*Pinus massoniana* L.) plantations were chosen because of their wide distribution in southern China, accounting for 45% of total plantation area in Guangdong Province (Kuang et al., 2008). In addition, Masson pine forests have relatively structural and spatial homogeneity, eliminating the confounding of other factors. We hypothesized that urbanization-induced environmental changes would increase soil C sequestration in these pine forests.

## 2 Materials and methods

### 2.1 Study region

This study comprised sites located throughout Guangdong Province, southern China (Fig. 1). The PRD economic region is the fastest developing area in the Province. The following environmental gradients have been related to patterns of urbanization extending from the core of PRD to its surrounding areas: (1) air temperature is approximately 0.5-2.0 °C higher in the core of PRD than in its surroundings due to the effect of "urban heat island" (Mai et al., 2011; Dou et al., 2011); (2) $CO_2$ emissions are relatively elevated in PRD, accounting for 70% of total emissions in Guangdong Province (Liu, 2009); (3) rates of N deposition vary from approximately 46 kg $ha^{-1}y^{-1}$ toward the core of PRD to < 20 kg $ha^{-1}y^{-1}$ in the most distant rural areas (Huang et al., 2012; Kuang et al., 2011); and (4) annual average precipitation is also higher in urban area than in surrounding areas (Li et al., 2009).

Because the pattern of urbanization of this region is not always linear, we combine both distance from center and land-use status to determine our gradients. We initially use distance to define four urbanization classes in this study region: (1) urban, 0-65 km form urban core; (2) urban/suburban, 65-130 km form urban core; (3) suburban/rural, 130-195 km from urban core; (4) rural, 195-260 km from urban core (Fig. 1). We further divided each class into 10 subzones of equal area. In each class we randomly chose 3 or 4 subzones to locate our sampled forests based on a land-use map. In total, 14 forests were selected in this study — three in the urban class (Huolushan, Maofengshan, and Shunfengshan, abbreviated to HLS, MFS, and SFS, respectively), four in the urban/suburban class (Heshan (HS), Dinghushan (DHS), Guanyinshan (GYS), and Xiangtoushan (XTS)), four in the suburban/rural class (Heishiding (HSD), Shimentai (SMT), Yunjishan (YJS), and Dachouding (DCD)), and three in the rural class (Huaiji (HJ), Dadongshan (DDS), and Wuzhishan (WZS) (Fig.1). Longitude of these forests ranges from E111°54′19.78″ to E114′25′37.54″, and latitude ranges from N22° 40′ 13.31″ to N24° 46′ 40.25″ (Table S1). Annual precipitation ranges from 1566 to 2133 mm, and mean annual air temperature ranges from 19.45 to 22.2 °C in the study region (Table S1).

All pine plantations used in this study had remained unmanaged following planting. Several criteria were used in site selection to ensure comparability among forests: (1) no disturbance after planting, including fire, insect infestations, logging, and fertilization; (2) stand age between 40 and 60 years; (3) stand density between 600 and 800 trees $ha^{-1}$ (Table S1); (4) soils of lateritic red earth (Ultisols in USDA soil taxonomy or Acrisols in the FAO soil classification). In addition, sampling was carried out in the center of the selected site to avoid edge effects.

**2.2 Soil sampling**

Soil sampling was conducted during January to May of 2011. In each forest site, three random subplots (5m×5m) were selected to sample soil from three soil layers (0-10 and 10-20 and 20-40 cm depths) using a 10-cm inside diameter (ID) corer. Soil samples passed through a 2 mm sieve, and roots and plant residues were removed. Soil organic carbon (SOC) was determined by dichromate oxidation and titration with ferrous ammonium sulfate (Walkley and Black, 1934). Soil total nitrogen (TN) was measured using the micro-Kjeldahl method (Jackson, 1964). For bulk density determination, soil was collected in a 0.25 $m^2$ × 0.5 m deep pit in each subplot using a 5-cm ID corer. Bulk density measures were used to calculate SOC content.

Soil microbial biomass carbon (MBC) was estimated by chloroform fumigation extraction technique (Vance et al., 1987). Soluble C was extracted using a 0.5 M $K_2SO_4$ solution from10-g soil samples before and after fumigation. Extracts were analyzed for total dissolved C using a total C analyzer (Shimadzu model TOC-500, Kyoto, Japan). Soil MBC was calculated as the difference in extractable C between fumigated and non-fumigated soil, divided by 0.45. Soil extractable dissolved organic carbon (DOC) was measured on the same samples used for the analysis of MBC, and calculated as the $K_2SO_4$-extractable C concentration.

**2.3 Soil density fractions**

Soil C was separated into two fractions using a density fraction method: (1) light fraction (LF), which tends to have younger soil C pools and includes undecomposed or partly decomposed organic residues and micro-biomass (Christensen et al., 2001); (2) heavy fraction (HF), which generally contains older soil C pools and includes C associated with mineral surfaces or concealed within micro-aggregates (Trumbore, 1993). Methodology for soil C fractionation followed McLauchlan and Hobbie (2004) with alterations as noted. Approximately 15 g of air-dried soil was weighed into a 100 ml centrifuge tube with 50 mL NaI (a density of 1.7 g $cm^{-3}$). Tubes were centrifuged at 1000 rpm for 10 min. The materials floating on the surface of tubes (LF) were decanted into a vacuum filter unit with 0.45 um nylon filter paper. This process was repeated until no floating material remained. The materials remaining at the bottom (HF) of the centrifuge tube were also rinsed into the vacuum filter unit. All samples on the filter paper were washed with 75 mL of 0.01 mol/L $CaCl_2$, followed by at least 75 mL of distilled water. The light and heavy materials were dried at 60°C for 48 h and weighed. All samples passed a 60-mesh sieve and analyzed for SOC and TN concentration as previously described.

## 2.4 Fine root biomass

Root cores were collected using a 10-cm ID corer from 0-10 cm soil layer. Fine roots (≤ 2 mm diameter) were sorted from washed cores by hand into living and dead components following procedures from Silver and Vogt (1993). Root samples were washed by distilled water, oven dried, and measured for living and dead fine roots biomass. The SOC and TN of live fine root samples were also analyzed as described.

## 2.5 Statistical analysis

All data analyses were carried out using SAS software (SAS Institute Inc., Cary NC, USA). One-way analysis of variance (ANOVA) was performed to compare the differences among four urbanization classes (urban, urban/suburban, suburban/rural, and rural) in fine root biomass, fine root C and N concentration, and soil respiration. Two-way ANOVA was used to test differences among urbanization classes and soil depths in the variables which were measured in multiple soil layers. Correlation and regression analyses were used to examine relationships between variables and distance from urban center to rural. Statistical significant differences were set at $P < 0.05$ unless otherwise stated. Mean values are expressed ±1 standard error of the mean.

# 3 Results

## 3.1 SOC and TN concentrations

SOC and TN concentrations both varied significantly with urbanization class, with both increasing from urban to rural condition (Table 1). Significant and positive correlation existed between SOC concentrations, soil TN concentrations and distance from urban to rural in all soil depths ($0.52 \leq R^2 \leq 0.66$, all $P < 0.001$). Distance explained approximately 24 - 31% and 21- 36% of changing for SOC and soil TN among sites, respectively. Two-way ANOVA showed that urbanization-induced environmental changes significantly reduced SOC and TN concentrations in urban compared with those in suburban and rural sites in all soil depths (Table 1, all $P < 0.05$). As a result, no significant difference among gradient classes was shown for the soil C: N ratio in any soil layer (Table 1, all $P > 0.05$).

### 3.2 SOC content

When SOC was calculated as content (i.e., as Mg $ha^{-1}$) it increased significantly from urban to rural conditions, exhibiting a positive linear relationship with distance across all soil depths (Fig 2 A, $R^2 = 0.717$, $P < 0.001$). Two-way ANOVA showed that SOC content significantly increased from urban to rural at 0-10 cm depth (Fig 2B, $P < 0.001$), but not at 10-20 and 20-20 cm depths (Fig 2B, $P$ = 0.5060 and 0.0821, respectively). When calculating SOC content to 40 cm depths, the mean SOC content were 64.87 ± 4.17, 79.12 ± 11.7, 93.83 ± 8.71, and 96.43 ± 6.60 Mg $ha^{-1}$ in urban, urban/suburban, suburban/rural and rural sites, respectively.

### 3.3 Soil density fractions

LF and HF showed different patterns along the urban-to-rural gradient. HF comprised > 94% of total soil mass and contained the majority of soil C content (approximately 70 - 85%) for all sites combined (Table 2). Mass proportion of LF and HF, LF organic carbon (LF-OC) concentrations, and the LF-OC content did not vary significantly along the gradient (Table 2). In contrast, heavy fraction organic carbon (HF-OC) concentration increased from urban to rural conditions in 0-10 and 10-20 cm soil layer (Table 2, both $P < 0.0001$). N concentrations in LF showed no significant difference among four urbanization classes, but significantly increased in HF from urban to rural in both 0-10 and 10-20 cm soil layer (Table 2, $P = 0.0001$ and 0.0244, respectively). No significant change was observed for the C: N ratio of LF and HF in two soil layers (Table 2, both $P > 0.05$).

### 3.4 Fine root, microbial biomass C, and extractable DOC

Live and dead fine root biomass exhibited similar patterns along the urban-to-rural gradient. Live fine root biomass was significantly higher than dead root biomass ($P < 0.001$, n = 14), and comprised approximately 70% of total fine root biomass (live plus dead). Live, dead and total fine root biomass was all significantly lower in urban sites than in other urbanization classes (Fig 4A). Live fine root C concentration exhibited no significant difference among four gradient classes, but N concentrations of live fine root increased significantly from urban to rural (Fig 5, $P < 0.0001$). C:N ratios declined from 44 ± 4 in urban sites to 40 ± 3, 33 ± 2 and 28 ± 4 in urban/suburban, suburban/rural, and rural sites, respectively ($P < 0.0001$).

Microbial biomass C decreased significantly from urban to rural sites in 0-10 cm soil layer (Fig 4bB, $P < 0.05$), but not significantly in 10-20 and 20-40 cm (Fig 4B, both $P > 0.05$). Conversely, the extractable DOC was not significantly different among urbanization classes in any soil layer (Fig 4C, $P > 0.05$ for each layer).

## 4 Discussion

SOC content ranged along the urban-to-rural gradient from 64.87 to 96.43 Mg $ha^{-1}$ in top 40 cm soil, well within the range (41.74 to 102.17 Mg $ha^{-1}$) reported for pine forests in Guangdong province and other subtropical regions of China (Fang and Mo 2002; Kang et al., 2006; Zheng et al., 2008; Jiang et al., 2011). Our results suggest that urbanization-induced environmental change has significantly decreased soil C content (Fig. 2B), rejecting our initial hypothesis and contradicting results from other studies. Pouyat et al. (2002) analyzed soil in New York red oak (*Quercus rubra* L.) forests and showed that soil C content significantly increased in urban sites compared to those in rural sites. In a semi-arid tropical desert ecosystem, similar results were also found by Koerner et al. (2010) along an urban-to-rural gradient in Phoenix, Arizona.

Although the reasons for our observed pattern are not clear, we suggest two possible explanations. First, C input may be decreased in urban sites due to the reduction of belowground root input to the soil. We found that fine root biomass was significantly lower in urban sites than those in suburban and rural sites (Fig. 4A). Indeed, C input via fine roots can equal C input from above-ground production (Nadelhoffer and Raich 1992). Furthermore, because annual productivity of fine roots typically decreases with excess N availability (Nadelhoffer, 2000), it is likely that decreased fine root production arose from higher N deposition in more urbanized areas (Gilliam, 2006, 2007).

Second, soil C loss from urban sites may be enhanced by increasing SOM decomposition. Decomposition of SOM can be influenced by a variety of factors, including organic matter quality, microbial activity, and microclimate (Chapin et al., 2002). In our study, organic matter quality did not appear to change with degree of urbanization, since there were no significant differences in soil

C:N ratio along the urban-to-rural gradient (Table 1). There was, however, a significant increase in microbial biomass in urban sites (Fig. 4B), indicating a potential increase in microbial activity. Meanwhile, the elevated air temperatures associated with urban sites would also increase SOM decomposition. Pouyat et al. (2002) suggested that the elevated temperature in urban areas increased litter decay rate, and that the magnitude even can offset increased litter input to the soil.

Although there were no significant differences in DOC among four gradient classes (Fig. 4C), some studies have reported that land-use change and land management can increase DOC fluxes in urban areas (Aitkenhead-Peterson et al., 2009; Williams et al., 2005). Compared to such anthropogenic influences, our results suggest that the effects of urbanization on soil DOC flux may be negligible.

Decreases in soil C storage in urban areas appears largely driven by the change in HF-OC pool (often considered passive C), rather than in LF-OC pool (labile C) (Fig. 3). Contrary to our results, other work has found that higher total passive C and lower labile C in soil from urban forests compared to soil from rural forests (Groffman et al., 1995), which was attributed to decreasing SOM recalcitrance, which was strongly linked with the reduction of air pollution and earthworm activity.

It has been suggested that the recalcitrance of SOM would increase with the formation of stable organo-mineral complexes via adsorption reactions (Sollins et al., 1996). We found that N concentration of HF was higher in rural sites than in suburban and urban sites (Table 2), suggesting that increasing amounts of N-rich material was adsorbed into mineral soil, possibly forming stable organo-mineral complexes in rural areas. N-rich proteinaceous compounds are important in the formation of organo-mineral complexes (Kleber et al., 2007). We suggest that these N-rich materials may arise from dead roots, considering that both dead fine root biomass and root N concentrations increased toward rural sites (Fig. 5). In addition, the enzyme-kinetic hypothesis predicts that degradation of low-quality substrate (recalcitrant molecular structure) has a higher temperature sensitivity compared to labile substrate because the former requires higher total activation energy to fully mineralize substrate (Bosatta and Agren 1999). Therefore, higher temperature in urban areas is likely cause accelerated decomposition of HF-C and may be another reason for the lower HF-C content in urban sites.

In conclusion, we measured the forest SOC content along an urban-to-rural gradient in Guangdong province, southern China. We found SOC content was significantly lower in urban areas than those in suburban and rural areas. It was suggested that decreased fine root biomass and a potential increased SOC decomposition were the possible reasons for this lower soil C pool in urban forests. We further found that HF-OC content also increased from the urban to the rural, which was the main driver of the change of total soil C pool. By contrast, LF- OC had not significant change in this study. These results are contrary to the general belief and the earlier studies, suggesting that urbanization-induced environmental changes may decrease soil C sequestration in the studied forests. Our findings would be typical for tropical plantation forests, however, the results and corresponding control mechanism should be further validated in various ecosystems and regions in the future.

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**Table 1.** Comparison of SOC (%), TN (%), soil C/N ratio and soil bulk density (g $cm^{-2}$) (in 0-10,10-20, and 20-40 cm soil layers) among four urbanization gradient classes.

| Soil depth (cm) | Urbanization classes | SOC (%) | | TN (%) | | C/N ratio | Soil bulk density (g $cm^{-3}$) | |
|---|---|---|---|---|---|---|---|---|
| 0-10 cm | Urban | 2.10 (0.13) | a | 0.19 (0.02) | a | 10.92 (1.05) | 1.25 (0.17) | a |
| | Urban/Suburban | 2.63 (0.47) | a | 0.23 (0.03) | ab | 12.03 (2.09) | 1.22 (0.14) | a |
| | Suburban/Rural | 3.75 (0.40) | b | 0.28 (0.04) | bc | 13.47 (2.91) | 1.04 (0.13) | b |
| | Rural | 3.99 (0.63) | b | 0.31 (0.03) | c | 12.91 (2.52) | 1.03 (0.05) | b |
| 10-20 cm | Urban | 1.33 (0.16) | a | 0.10 (0.01) | a | 14.28 (2.55) | 1.41 (0.10) | a |
| | Urban/Suburban | 1.59 (0.48) | ab | 0.11 (0.02) | a | 14.98 (3.12) | 1.34 (0.12) | ab |
| | Suburban/Rural | 2.04 (0.40) | ab | 0.15 (0.03) | ab | 14.18 (2.92) | 1.15 (0.08) | ab |
| | Rural | 2.19 (0.06) | b | 0.15 (0.01) | b | 15.46 (1.07) | 1.19 (0.03) | b |
| 20-40 cm | Urban | 0.81 (0.09) | a | 0.05 (0.02) | a | 18.05 (1.23) | 1.48 (0.10) | a |
| | Urban/Suburban | 0.93 (0.20) | a | 0.05 (0.02) | a | 18.23 (1.02) | 1.41 (0.06) | ab |
| | Suburban/Rural | 1.47 (0.20) | b | 0.08 (0.01) | ab | 18.28 (1.03) | 1.21 (0.13) | ab |
| | Rural | 1.51 (0.12) | b | 0.08 (0.02) | b | 18.34 (0.94) | 1.26 (0.01) | b |

Notes: The different letters indicate significant differences at $P < 0.05$ level, and no letters indicate no significant differences among different urbanization gradient classes, respectively (SNK test). Values are means with S.E. in parentheses (N = 3 for urban and rural, N = 4 for urban/suburban and suburban/rural).

**Table 2.** Characteristics of two soil fractions.

| Soil fraction | Depth (cm) | Urban classes | C (%) | N (%) | C/N ratio | Percent of bulk soil mass (%) | Percent of bulk soil C (%) |
|---|---|---|---|---|---|---|---|
| LF | 0-10 | Urban | 25.96 (3.66) | 0.93 (0.11) | 28.04 (0.91) | 3.62 (0.53) | 28.80 (4.02) |
| | | Urban/Suburban | 21.50 (3.84) | 0.87 (0.13) | 25.29 (4.01) | 3.54 (0.99) | 28.25 (5.34) |
| | | Suburban/Rural | 26.72 (5.89) | 0.91 (0.09) | 29.48 (4.31) | 4.10 (1.34) | 27.22 (5.47) |
| | | Rural | 21.68 (2.92) | 0.81 (0.05) | 26.46 (2.46) | 5.87 (1.33) | 26.40 (4.04) |
| | 10-20 | Urban | 25.29 (3.97) | 0.64 (0.03) | 40.67 (7.68) | 1.06 (0.06) | 19.81 (1.48) |
| | | Urban/Suburban | 21.72 (2.50) | 0.57 (0.02) | 38.09 (5.52) | 1.35 (0.21) | 20.14 (1.40) |
| | | Suburban/Rural | 27.23 (5.30) | 0.66 (0.11) | 41.27 (5.43) | 1.19 (0.24) | 17.91 (1.62) |
| | | Rural | 25.55 (7.24) | 0.69 (0.12) | 36.74 (7.03) | 1.55 (0.56) | 15.06 (2.59) |
| HF | 0-10 | Urban | 1.66 (0.10) a | 0.12 (0.02) a | 14.30 (2.99) | 96.37 (0.48) | 71.20 (4.02) |
| | | Urban/Suburban | 1.99 (0.40) a | 0.15 (0.03) ab | 14.21 (2.12) | 96.45 (0.99) | 71.75 (5.34) |
| | | Suburban/Rural | 2.93 (0.54) b | 0.19 (0.04) bc | 14.97 (1.91) | 95.90 (1.34) | 72.78 (3.42) |
| | | Rural | 3.16 (0.44) b | 0.25 (0.07) c | 16.67 (3.10) | 94.12 (1.33) | 73.95 (4.49) |
| | 10-20 | Urban | 1.15 (0.18) a | 0.09 (0.01) a | 13.77 (2.32) | 98.94 (0.06) | 80.28 (1.48) |
| | | Urban/Suburban | 1.21(0.25) ab | 0.09 (0.02) a | 13.46 (2.93) | 98.64 (0.21) | 79.83 (1.40) |
| | | Suburban/Rural | 1.52(0.36) bc | 0.13 (0.03) ab | 11.71 (2.06) | 98.80 (0.24) | 82.54 (1.62) |
| | | Rural | 1.75 (0.22) c | 0.17 (0.09) b | 15.45 (4.14) | 98.44 (0.56) | 84.94 (1.15) |

Notes: The different letters indicate significant differences at $P < 0.05$ level, and no letters indicate no significant differences among different urbanization gradient classes, respectively (SNK test). Values are means with S.E. in parentheses (N = 3 for urban and rural, N = 4 for urban/suburban and suburban/rural).

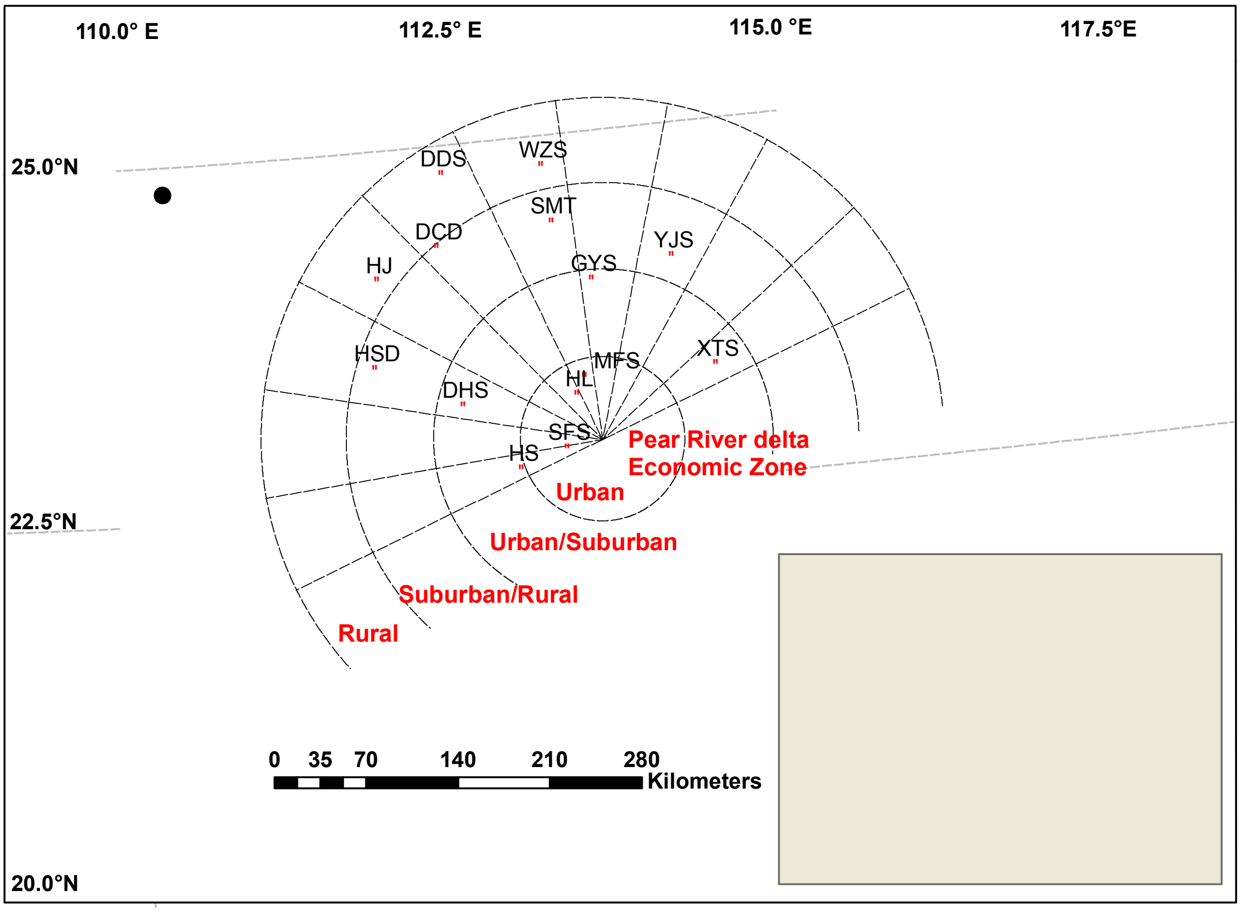


**Fig 1.** Location of our study sites in Guangdong province of southern China. A total of fourteen Masson Pine forests were selected along the transect. The detailed information for each forest is listed in Table S1

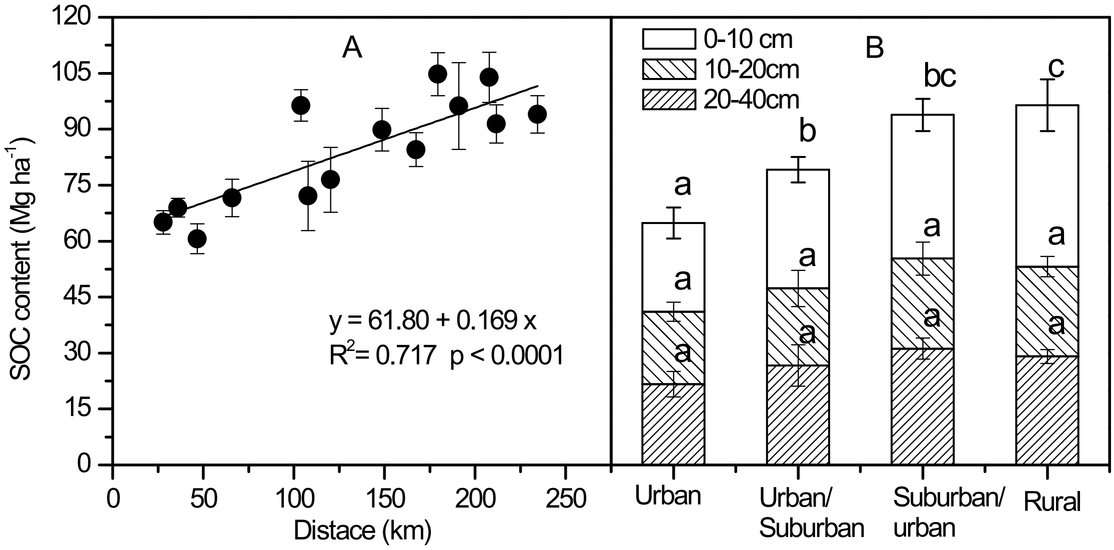


**Fig 2.** Change of SOC content in the top 40 cm soil. (A) correlation analysis of bulk SOC content (in 0-10 cm, 10-20 cm, and 20-40 cm soil layer) and the distance from urban to rural; (B) comparisons of SOC content among four urbanization gradient classes. Error bars indicate ± 1 S.E. (N = 3 for urban and rural, N=4 for urban/suburban and suburban/rural). Different letters denote significant difference ($P \leq 0.05$) between gradient classes (SNK test).

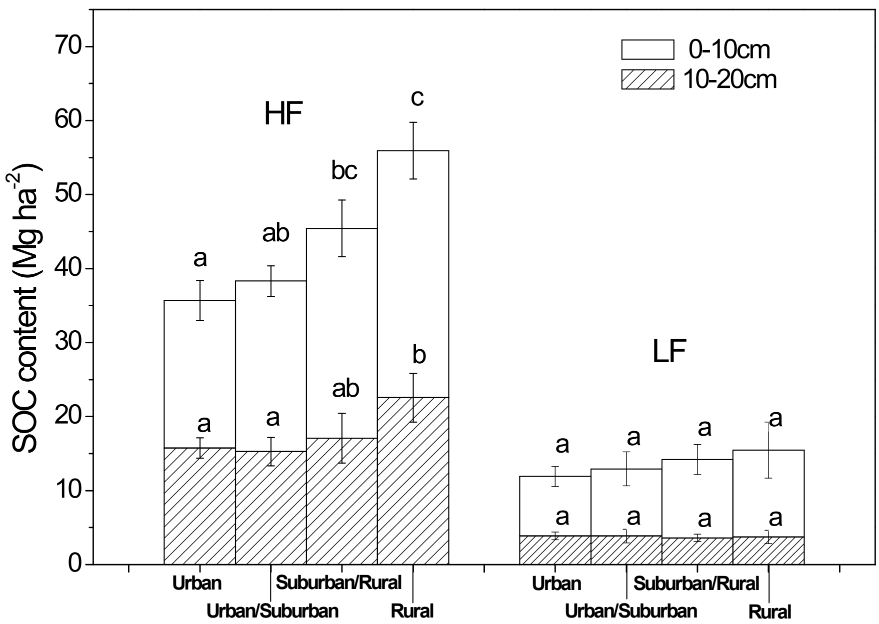


**Fig 3.** Comparisons of HF-OC and LF-OC content (in 0-10 and 10-20 cm soil layer) among four urbanization gradient classes. Error bars indicate ± 1 S.E. (N = 3 for urban and rural, N=4 for urban/suburban and suburban/rural). Different letters denote significant difference ($P \leq 0.05$) between gradient classes (SNK test).

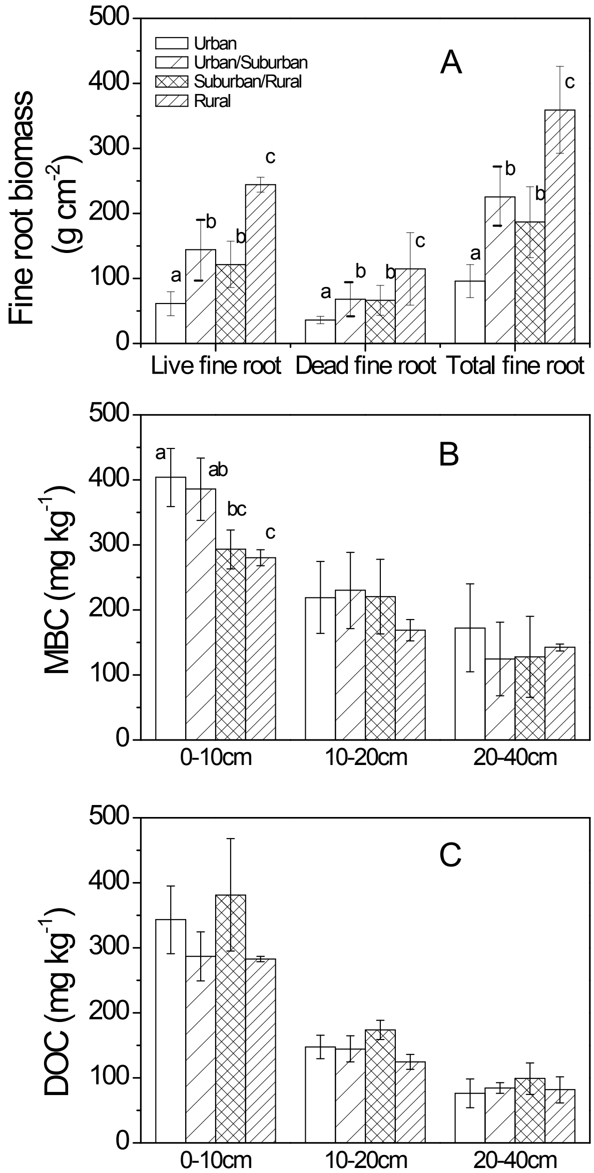


**Fig 4.** Comparisons of fine root biomass (A), MBC (B), DOC (C) among different urbanization gradient classes. Error bars indicate ± 1 SE (N = 3 for urban and rural, N=4 for urban/suburban and suburban/rural). Different letters indicates significant difference ($P \leq 0.05$) between gradient classes, and no letters indicate no significant differences ($P > 0.05$) among different urbanization gradient classes, respectively (SNK test).

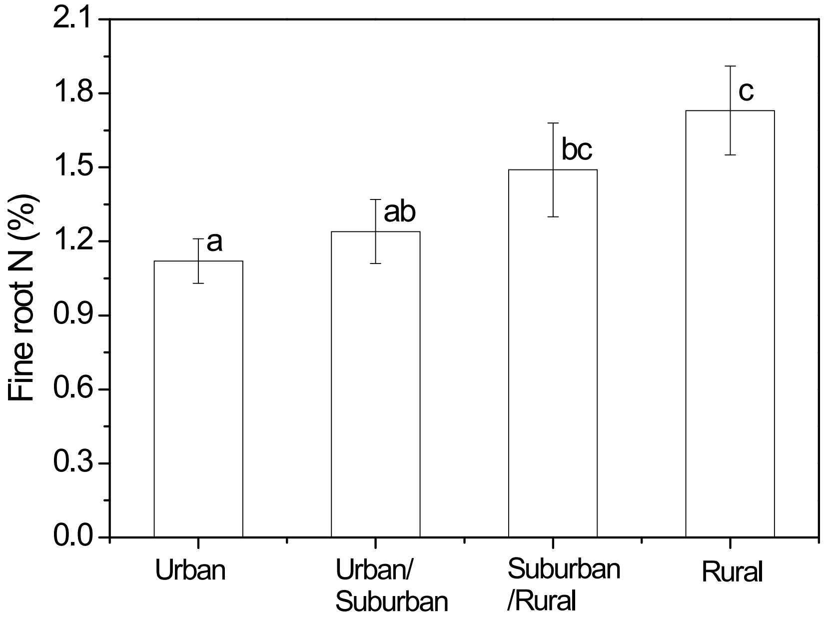


**Fig 5.** Comparisons of N concentration in live fine root (0-10 cm soil layer) among four urbanization gradient classes. Error bars indicate ± 1 S.E. (N = 3 for urban and rural, N=4 for urban/suburban and suburban/rural). Different letters denote significant difference ($P \leq 0.05$) between gradient classes (SNK test).

## Supplementary material

**Table S1. Site characteristics**

| Site (code) | Latitude (N) | Longitude (E) | Distance from urban core (km) | Elevation (m) | MAP (mm) | MAT (°C) | Stand density (trees $ha^{-1}$) | Tree age (year) |
|---|---|---|---|---|---|---|---|---|
| HLS | 23°10′53.30″ | 113°23′2.00″ | 36.1 | 45 | 1742 (351) | 22.09 (0.52) | 700 | 40 |
| MFS | 23°18′5.87″ | 113°27′0.57″ | 46.7 | 50 | 1742 (351) | 22.09 (0.52) | 700 | 40 |
| SFS | 22°49′7.65″ | 113°16′38.99″ | 28.0 | 48 | 1742 (351) | 22.09 (0.52) | 700 | 50 |
| HS | 22°40′13.31″ | 112°54′14.01″ | 66.0 | 60 | 1701 (283) | 21.15 (0.43) | 700 | 40 |
| DHS | 23°8′57.27″ | 112°31′3.07″ | 107.8 | 283 | 1625 (275) | 22.22 (0.47) | 800 | 60 |
| GYS | 23°58′9.34″ | 113°33′49.22″ | 120.3 | 385 | 2133 (383) | 20.95 (0.41) | 700 | 50 |
| XTS | 23°18′26.87″ | 114°25′37.54″ | 103.8 | 366 | 1730 (340) | 22.01 (0.49) | 700 | 40 |
| HSD | 23°27′42.85″ | 111°54′19.78″ | 179.3 | 400 | 1690 (265) | 20.99 (0.47) | 700 | 50 |
| SMT | 24°23′7.47″ | 113°18′8.49″ | 167.5 | 56 | 1675 (243) | 19.45 (0.43) | 700 | 40 |
| YJS | 24°4′55.65″ | 114°10′18.33″ | 148.6 | 462 | 1758 (314) | 19.93 (0.50) | 700 | 40 |
| DCD | 24°16′58.67″ | 112°25′25.81″ | 191.0 | 891 | 1597 (328) | 19.65 (0.45) | 700 | 40 |
| HJ | 24°4′7.45″ | 111°57′50.40″ | 207.8 | 432 | 1597 (328) | 19.65 (0.45) | 700 | 40 |
| WZS | 24°46′40.25″ | 113°15′28.59″ | 211.7 | 500 | 1566 (281) | 20.38 (0.39) | 750 | 60 |
| DDS | 24°46′17.29″ | 112°30′3.17″ | 234.5 | 815 | 1597 (328) | 19.65 (0.45) | 700 | 60 |

Notes: MAP = mean annual precipitation, for the years 1978 - 2011; MAT = mean annual temperature, for the years 1978 - 2011; Temperature and precipitation in each sites interpolated from the nearest meteorological station data. Latitude, longitude and elevation are from GPS readings taken on site.