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Loss of labile organic carbon from subsoil due to land-use changes in subtropical China

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ABSTRACT

Topsoil carbon (C) stocks are known to decrease as a consequence of the conversion of natural ecosystems to plantations or croplands; however, the effect of land use change on subsoil C remains unknown. Here, we hypothesized that the effect of land use change on labile subsoil organic C may be even stronger than for topsoil due to upward concentration of plantations and crops root systems. We evaluated soil labile organic C fractions, including particulate organic carbon (POC) and its components [coarse POC and fine POC], light fraction organic carbon (LFOC), readily oxidizable organic carbon, dissolved organic carbon (DOC) and microbial biomass down to 100 cm soil depth from four typical land use systems in subtropical China. Decrease in fine root biomass was more pronounced below 20 cm than in the overlying topsoil (70% vs. 56% for plantation and 62% vs. 37% for orchard. respectively) driving a reduction in subsoil labile organic C stocks. Land use changes from natural forest to Chinese fir plantation, Chinese chestnut orchard, or sloping tillage reduced soil organic C stocks and that of its labile fractions both in top and subsoil (20–100 cm). POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Fine POC, LFOC and microbial biomass can be useful early indicators of changes in topsoil organic C. In contrast, LFOC and DOC are useful indicators for subsoil. Reduced proportions of fine POC, LFOC, DOC and microbial biomass to soil organic C reflected the decline in soil organic C quality caused by land use changes. We conclude that land use changes decrease C sequestration both in topsoil and subsoil, which is initially indicated by the labile soil organic C fractions.

1. Introduction

Land use and land use changes (LULUC) in tropical and subtropical areas, including forest conversion, capitalized agricultural intensification and animal husbandry expansion, represent major anthropogenic contributions to greenhouse gas emissions (Harris et al., 2012; IPCC, 2013). Tropical and subtropical Asia concentrates the fastest and most dramatic LULUC in the world, mainly as consequences of rapid agricultural expansion and increasing population pressure (Houghton, 2002; Carlson et al., 2012). The average rate of deforestation in tropical Asia during the 1990s reached up to 5.6×10^6 ha yr^{-1}, resulting in the emission of 1.0 Pg C yr^{-1} into the atmosphere (Houghton, 2002).

Tropical and subtropical aboveground biomass has received much research attention because these regions are highly productive with dense C stocks (Lewis et al., 2009; Huntingford et al., 2013). However, comprehensively studies regarding underground soil organic C (SOC) content and fractions, lability and response to land use change remain scarce.

Highly weathered tropical and subtropical soils present the deepest profiles and largest volumes among soils worldwide, accounting for nearly half of the global soil C stock in the top 3 m of soil (Richter and Markewitz, 1995; Jobbágy and Jackson, 2000). Unfortunately, most studies on the effect of LULUC on SOC have focused on the topsoil layer (0–20 cm) being the layer of soil containing the highest levels of SOC and the greatest microbial

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activity (e.g., Saha et al., 2011; Nahrawi et al., 2012; Wang et al., 2013; Umrit et al., 2014). In contrast, the response of SOC and its fractions in subsoil to land use change has received less attention (Rumpel and Kögel-Knabner, 2011; Schmidt et al., 2011; Harper and Tibbett, 2013), mainly because subsoil SOC has been assumed to be old, stable, inert and insensitive to LULUC. Several recent studies have focused on the level of SOC lability in subsoil and its dynamic response to land use and management practices in tropical and subtropical regions (e.g., Veldkamp et al., 2003; Conti et al., 2014; Mobley et al., 2015).

Soil labile organic C (LOC) is more sensitive to short term land use change than SOC (Degryze et al., 2004; Yang et al., 2009a; Liang et al., 2012); however, the magnitude and characteristics of each LOC fractions, vary depending on the direction of land use change and the fractionation approach used (Strosser, 2010). Measured LOC fractions are heterogeneous in terms of turnover times, chemical compositions, and functions (von Lützow et al., 2007), and therefore, they may respond differently to short term LULUC and management practices. To date, several studies have analyzed the response of topsoil LOC fractions to land use change in tropical and subtropical Asia (e.g., Deng et al., 2009; Yang et al., 2009a; Wang et al., 2013); however, comparatively fewer studies have focused on the response of subsoil C fractions.

Subsoil LOC stocks can be affected by LULUC in different ways: (i) new aboveground vegetation can influence root distribution, litter fall quality, phenology, and litter layer depth, affecting fresh C supplies and soil C stability in the subsoil (Fontaine et al., 2007; Wang et al., 2014a); (ii) intensive management, including site preparation, terracing tillage, and irrigation can turn over soil horizons, destroy aggregates, and expose subsoil C to air and decomposers (Salomé et al., 2010; Wei et al., 2013); (iii) common agricultural practices such as fertilization, prescribed burning, and weeding may provide fresh C and nutrients to subsoil microbial communities inducing a priming effect (Kuzyakov, 2010); and (iv) strong erosion, a common consequence of land use change in hilly regions with abundant rainfall and non-stable aggregates, may lead to the exposure of subsoil and the erosion of lighter organic compounds (van Noordwijk et al., 1997; Wang et al., 2014b).

The subtropical region of China extends over 250 million hectares, presenting evergreen broadleaved forests as the climax vegetation. Commercial timber exploitation, cash crop production and the animal husbandry industry have developed rapidly in this region over the past few decades. Large areas of evergreen broadleaved forest have been slashed, burned and subsequently replaced by highly productive plantations, orchards, and sloping tillage. These rapid land use changes have led to serious environmental problems, including water-induced soil erosion, soil fertility decline, productivity loss, and decrease in ecosystem resilience (Yang et al., 2009b; Sheng et al., 2010). In addition, subtropical China is characterized by widespread mountain and hilly landforms with steep slopes, frequent heavy rainfall, and severe soil erosion. As a consequence, Chinese subtropical ecosystems are highly vulnerable to human disturbance. The nature, extent and driving forces of land use change may differ significantly between subtropical mountainous areas and tropical plains and lowlands (e.g., the Amazon Basin). Yet, only a few studies have focused to date on the response of SOC and its labile fractions in soil, in particular in the subsoil, to land use change in subtropical regions.

In this study, we assessed the predominant land use trajectories of four land use systems (natural forest, Chinese fir plantation, Chinese chestnut orchard and sloping tillage) with well-known site history in the east of the Hunan Province. The specific objectives of this study were to (i) quantify the responses of SOC, in particular LOC fractions, to land use change in topsoil (0–20 cm) and subsoil (20–100 cm); (ii) assess the sensitivity of LOC fractions isolated by various fractionation methods as early indicators of SOC alterations due to land use change; and (iii) use LOC/SOC ratios to evaluate the effect of land use change. We tested the following hypotheses: (i) land conversion into plantations decreases SOC stock, in particular the labile fractions, in topsoil and subsoil below 20 cm; (ii) LOC fractions can be used as sensitive indicators of SOC alterations due to land use change; and (iii) fine root C input controls LOC stocks in subsoil.

2. Materials and methods

2.1. Site description

The study site is located in the Dawei Mountain National Forest Park, Liuyang City, Hunan Province, central China (113°56′E, 28°25′N). The Forest Park covers 5053 ha. It adjoins Mufu Mountain on the northeast and Xuefeng Mountain on the southwest. The site climate is humid middle subtropical monsoon, with a mean annual air temperature of 17.7 °C (ranged from 2.5 °C in January to 28.0 °C in July) and a mean annual relative air humidity of 83%. The mean annual rainfall is 1800–2000 mm (~55% occurring from March to July) and the mean annual potential evapotranspiration (Penman–Monteith equation) is 1450 mm (Xu and Lu, 2002). In this study, we chose four typical land use systems: 1) natural forest (control), 2) Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) plantation, 3) Chinese chestnut (*Castanea mollissima*) orchard, and 4) sloping tillage. The plantation, orchard, and sloping tillage areas were transformed from natural forest in 2004. The sites selected were distributed adjacently within a small watershed in the Forest Park. All sites were similar in topography, regional climate, and soil type, and their elevations varied from 150 m to 165 m and the slopes ranged from 20° to 30°. For all sites in the four land uses, the soil was classified as red soil using the Chinese Soil Classification System (State Soil Survey Service of China, 1998), equivalent to hapludult in the USDA Soil Taxonomy (Soil Survey Staff of USDA, 2010) and Chromic Acrisol in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2014). The soil was acidic, and developed on deeply weathering product of medium grain granodiorite from the Sinian Period (Sheng et al., 2014). The soil profile was well developed and characterized by a B_t horizon with accumulation of low activity clays, reddish in color due to the accumulation of iron oxides. All sites were located on well-drained uplands with a soil profile deeper than 1.0 m. Table 1 shows the main characteristics and properties of the topsoil of the studied sites.

The natural forest was considered as the climax vegetation, known to have followed continuously its natural ecological succession for >300 years. The forest plant community was dominated by Camphor trees (*Cinnamomum camphora* (L.) J. Presl), mixed with *Liquidamba formosana* Hance, among others. The plantation, orchard, and sloping tillage sites were transformed from partially abandoned land after a natural forest clearing. No heavy machinery was involved in the land transformation process. After clear-cutting, all sites were prescribed burned and prepared for each specific land use. In 2004, a section of the main site was afforested with Chinese fir, another section was terraced along a ridge-less contour and divided into an orchard and an area of sloping tillage. The orchard was planted with Chinese chestnut, while sweet potatoes were grown annually in the sloping tillage area. Only the orchard and sloping tillage were regularly managed and treated with chemical fertilizers. The application rate of N, P, and K was 380, 32, and 66 kg ha^{-1} yr^{-1} in the orchard and 135, 26, and 96 kg ha^{-1} yr^{-1} in the sloping tillage area, respectively. Fertilizers were applied three times per year (May, late June, and early November) in the orchard, and twice a year (early April and late

Table 1
Site characteristics and topsoil (0–20 cm) physicochemical properties in different land use systems in subtropical China.

Properties	Land use systems			
	NF	CF	CO	ST
Elevation (m)	165	160	150	150
Slope (°)	30	28	20	20
Forest average DBH (cm)	11.2	8.2	9.1	nd
Mean tree height (m)	10.4	9.8	9.6	nd
Tree density (ha^{-1})	2600	2300	1200	nd
Basal area (m^2 ha^{-1})	94.3 a	66.7 b	38.4 c	nd
Depth of litter layer (cm)	4.0	2.5	3.0	0.5
Standing stock of litter layer (t ha^{-1})	7.64 a	3.63 b	4.05 b	0.10 c
Fine root biomass at 0–60 cm depth (t ha^{-1})	8.78 a	3.23 b	4.40 b	0.11 c
Bulk density (g cm^{-3})	1.05 c	1.12 b	1.20 ab	1.32 a
pH (KCl)	3.9 a	3.7 a	3.7 a	3.8 a
Soil organic C (g kg^{-1})	19.12 a	13.39 b	13.48 b	12.31 b
Total nitrogen (g kg^{-1})	1.61 a	1.16 b	1.54 a	1.33 ab
$\delta^{13}C$ (‰)	−26.35	−26.39	−20.74	−24.78

NF, CF, CO, ST, DBH, and nd represent natural forest, Chinese fir plantation, Chinese chestnut orchard, and sloping tillage and mean tree diameter at breast height, and no data available, respectively. Different letters in the same row indicate significant difference among land use systems ($P < 0.05$).

August) in the sloping tillage area. Both orchard and sloping tillage were weeded and hoed by hand twice a year and irrigated periodically using a handheld sprinkler during prolonged drought seasons.

2.2. Experimental setup and sampling

We used a space-for-time substitution methodology which assumes that spatial and temporal variations are equivalent (Pickett, 1986). The experimental setup comprised triplicate 20 × 30 m fixed plots randomly distributed across each land use area in 2012.

The litter layer was carefully removed by hand from the surface before soil sampling. We collected ten soil cores (3.5 cm diameter) randomly from each experimental plot using a customized soil auger. The soil samples were obtained from a depth of 100 cm at a sampling interval of 20 cm, and subsequently mixed into a subsample for each layer. Visible plant debris and stones larger than 2 mm were removed immediately after sampling. In addition, 3 soil profiles were dug randomly in each plot, and 100-cm^3 columns at each sampling interval were sampled to determine soil bulk density.

Each soil subsample was divided into three portions. One portion was sieved at high moisture levels through a 2-mm mesh to ensure uniformity and homogeneity, and subsequently stored at 4 °C for microbial biomass (MBC) and dissolved organic C (DOC) analyses. A second portion was air-dried, crushed, and sieved through a 2-mm mesh before measuring particulate organic C (POC), light fraction organic C (LFOC) and readily oxidizable organic C (ROC). The remaining portion was sieved through a 0.149-mm mesh for SOC and total N analyses.

With the exception of the sloping tillage area, all trees of diameter at breast height (DBH) ≥4 cm in each plot were identified to the species level and measured using standard diameter measuring tapes. Fine root (<2 mm in diameter) biomass at 0–60 cm depth was determined using soil coring (Sheng et al., 2014). In addition, we measured thickness and standing stock of the litter layer in 3 randomly selected 1.0 × 1.0 m subplots in each land use plot.

2.3. Laboratory analyses

The light fraction material was extracted using NaI (Janzen et al., 1992). Briefly, 20 g of air-dried soil samples (<2 mm) were suspended in 50 ml NaI solution (1.70 g cm^{-3}), and shaken (250 rpm) for 6 h and subsequently centrifuged (4000 rpm) for 10 min. The supernatant was then filtered using 0.45 μm glass-fiber microfiltration membrane, and the remaining solution was collected for reuse. The separation method described above was repeated until no visible floating particles were left on the membrane. The particles on the membrane were collected, washed with 75 ml 0.1 mol L^{-1} $CaCl_2$ solution followed by a wash with 200 ml deionized water to remove any residual NaI, dried at 60 °C for 48 h, weighed, and stored as the light fraction material.

Particulate organic matter was separated as described by Cambardella and Elliott (1992): 20 g of air-dried soil samples (<2 mm) were dispersed in 100 ml 5 g L^{-1} sodium hexametaphosphate and shaken for 18 h. The suspension was then filtered through a 250-μm sieve followed by a 53-μm sieve. The material remaining on the sieves were thoroughly rinsed with deionized water, dried at 60 °C overnight, weighed, and stored as coarse (>250 μm) and fine (250–53 μm) particulate organic matter samples.

ROC was measured as described by Blair et al. (1995). Briefly, soil samples containing 15 mg C were weighed into plastic screw top centrifuge tubes and 25 ml 1/3 mol L^{-1} $KMnO_4$ were added to each tube. All tubes were tightly sealed, tumbled for 1 h and centrifuged for 5 min at 2000 rpm (RCF = 815 g). The supernatant was subsequently diluted with deionized water, and the C content was determined by colorimetry (Model SP-723, Spectrum Co., Shanghai, China) at 565 nm wavelength.

For measuring MBC, humid soil samples (25 g on an oven-dried basis) were fumigated with $CHCl_3$ vapor in a desiccator for 24 h. After removing any residual $CHCl_3$ by evacuation, the fumigated soils were extracted with 0.5 M K_2SO_4 for 30 min. Non-fumigated soils were extracted following the same procedure. All soil extracts were filtered and the organic C concentration in the extracts was determined using a TOC-analyzer (Phoenix 8000, Teledyne Tekmar Co., Mason, OH, USA). MBC per sample was estimated as $MBC = 2.22\ E_C$, where E_C = (organic C extracted from fumigated soil) − (organic C extracted from non-fumigated soil). Organic C extracted from non-fumigated soil was also considered as DOC (Wu et al., 1990).

Organic C and total N in bulk soil, light fraction materials, and POM were determined using an elemental analyzer (Vario EL III, Elementar Analysensysteme GmbH, Hanau, Germany). Soil pH was determined in 1 mol L^{-1} KCl solution at a soil-to-solution ratio of 1:2.5 (w/v) using a pH meter (Delta 320, Mettler-Toledo instruments Ltd., Shanghai, China). Soil bulk density was measured using the clod method (Blake and Hartge, 1986). Soil particle size distribution was estimated following the sieve-pipette method

(Gee and Bauder, 1986), and classified by the American Soil Texture Taxonomy, considering as sand the particle sizes within the 20–2000 μm range, silt as those in the 2–20 μm range, and clay for <2 μm (Soil Survey Staff of USDA, 2010).

2.4. Calculation of C stocks and sensitivity index

C stocks in bulk soil and labile fractions for each layer were calculated using equation (1) (Pan et al., 2003):

$$D = \mathrm{OC} \times \gamma \times h \times (1 - \delta) \times 10^{-1} \quad (1)$$

where D represents to organic C stock (t ha^{-1}), OC is the average organic C content in bulk soil and labile fractions (g C kg^{-1}), γ is the soil bulk density (g cm^{-3}), h is the sampling depth (20 cm), and δ is the gravel content (%).

Sensitivity index (SI) was defined as the reduction of LOC fractions after land use change, and was calculated as defined in equation (2) (Liang et al., 2012):

$$\begin{aligned} \mathrm{SI} = {} & (\text{labile C fractions in treatment} \\ & - \text{labile C fractions in control}) \\ & \times 100/\text{labile C fractions in control} \end{aligned} \quad (2)$$

2.5. Statistical analysis

All statistical analyses were performed using SPSS software (SPSS 13.0 for Windows, SPSS Inc., Chicago, IL, USA). Each plot was considered as an experimental unit, and the replicated data were averaged by plots for the analyses. Prior to conducting one-way repeated-measures (ANOVA) analysis, all variables were checked for normal distribution (Kolmogorov–Smirnov test) and homogeneity (Levene's test). Data of stocks of SOC and labile organic C were transformed to natural logarithms to achieve homogeneity. ANOVA were performed to compare SOC and LOC stocks among land use systems using Turkey's HSD test. The relation between subsoil LOC fractions with fine root biomass at 20–60 cm depth, and SOC in subsoil was examined using linear regression. All results were represented as mean value ± standard error and the statistical significance was calculated at 5% level unless otherwise mentioned.

3. Results

3.1. Plant biomass and soil basic properties

Total plant biomass decreased significantly following land use change. Basal area, standing stock in the litter layer, and fine root biomass at 0–60 cm depth decreased significantly following the conversion from natural forest to Chinese fir plantation, by 29%, 53% and 63%, respectively, and to Chinese chestnut orchard, by 59%, 47% and 50%, respectively (Table 1). For the sloping tillage plots, standing stock of the litter layer and fine root biomass at 0–60 cm depth decreased by up to 99% compared with natural forest. Fine root biomass below 20 cm decreased more strongly compared to that in the topsoil (70% vs. 56% for plantation and 62% vs. 37% for orchard) (Fig. 1).

Topsoil bulk density increased by 0.2 and 0.3 g cm^{-3} following the conversion from natural forest to orchard and sloping tillage, respectively (Table 1). Total N content also decreased by 28% after natural forest conversion to plantation.

3.2. SOC stocks in top and subsoil

SOC stock in topsoil markedly decreased following land use change, by 35% (plantation), 32% (orchard) and 25% (sloping tillage) (Fig. 1). SOC stock below 20 cm depth was also significantly reduced by 23% with the conversion to plantation, 29% to orchard, and 40% to sloping tillage. In total, after conversion, SOC stock in 0–100 cm soil decreased by 26% (plantation), 30% (orchard), and 35% (sloping tillage). These results show a remarkable loss of SOC following land use changes not only in the topsoil, but also in subsoil deeper than 20 cm down to 100 cm.

3.3. LOC fraction stocks in top and subsoil

The stocks associated with the different LOC fractions in topsoil and subsoil responded differently to land use changes. POC decreased by 15%, 38%, and 33% at 0–20 cm depth, and by 10%, 12%, and 18% at 20–100 cm depth following natural forest conversion to plantation, orchard, and sloping tillage, respectively (Fig. 2). Consequently, POC stock in topsoil was more sensitive to land use change than that in subsoil (Fig. 3). Regarding the different POC components, only fPOC stock in 0–20 cm topsoil decreased by 21%, 53%, and 51% after natural forest conversion to plantation, orchard, and sloping tillage, respectively (Fig. 2). This implied that the reduction of POC stock after land use change mainly resulted from the loss of topsoil fPOC, which, consequently, could be used as a sensitive indicator to detect SOC changes. Noticeably, fPOC stock in subsoil below 40 cm increased by 11–74% following the land use change, indicating that changes in POC fractions in subsoil may follow the opposite direction to those in topsoil (Fig. 3).

Significant loss of LFOC occurred not only in topsoil, but also in subsoil below 20 cm following land use change (Fig. 4). The topsoil showed a greater reduction in LFOC stock than did subsoil following the conversion of natural forest to orchard and sloping tillage. LFOC appeared to be more sensitive to land use changes than SOC both in top and subsoil (Fig. 3). The decrease in ROC stock through the soil

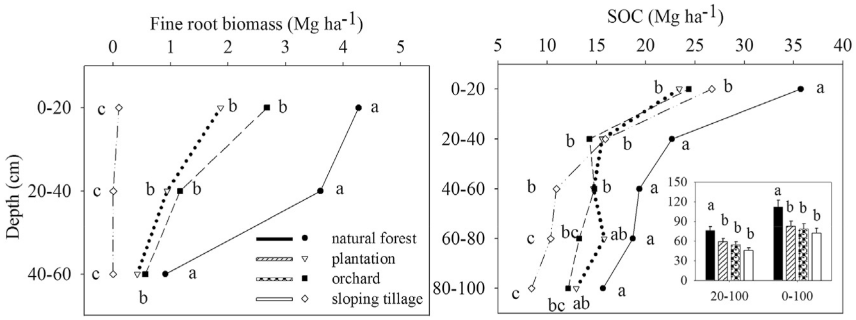

Fig. 1. Fine root biomass (left) and soil organic C stocks (right) in relation to depth and land use systems in subtropical China. Letters indicate significant differences among land use systems ($P < 0.05$).

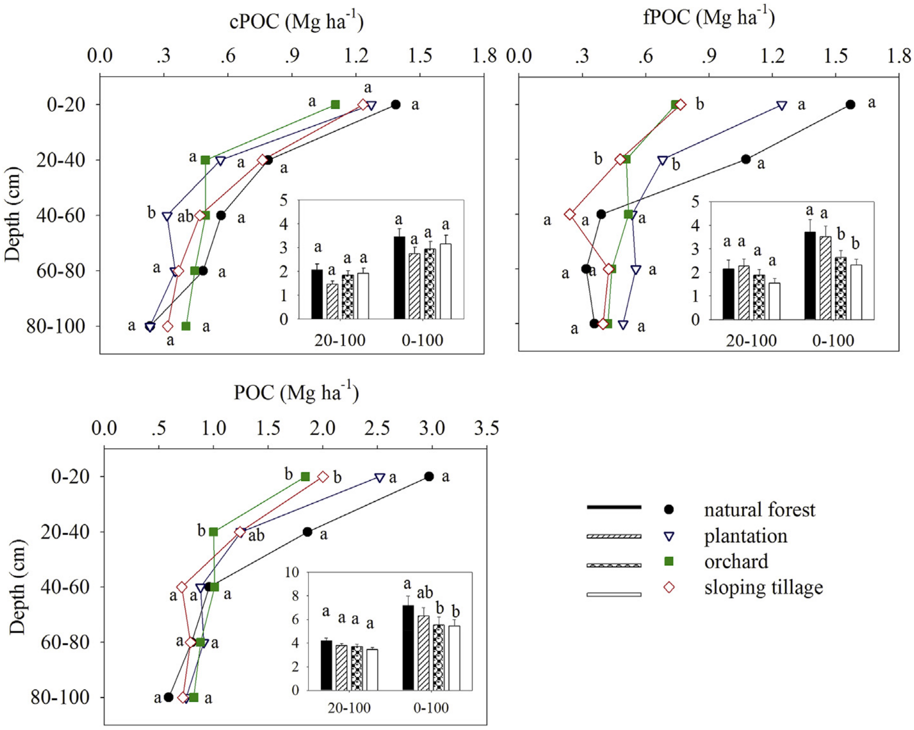

Fig. 2. POC stocks and those of its components (cPOC, fPOC) in relation to depth and land use systems in subtropical China. POC, cPOC, and fPOC represent particulate organic C, coarse particulate organic C, and fine particulate organic C, respectively. Letters represent significant differences among land use systems ($P < 0.05$).

depth profile following land use change was smaller than that of LFOC (Fig. 4). ROC stocks did not differ significantly between natural forest and sloping tillage areas, suggesting that ROC stock was relatively insensitive to land use change.

The DOC stock in the topsoil decreased by 29% and 78% following the conversion of natural forest to plantation and orchard, respectively, and subsoil DOC stocks decreased even more dramatically following land use change (Fig. 4). MBC stock decline

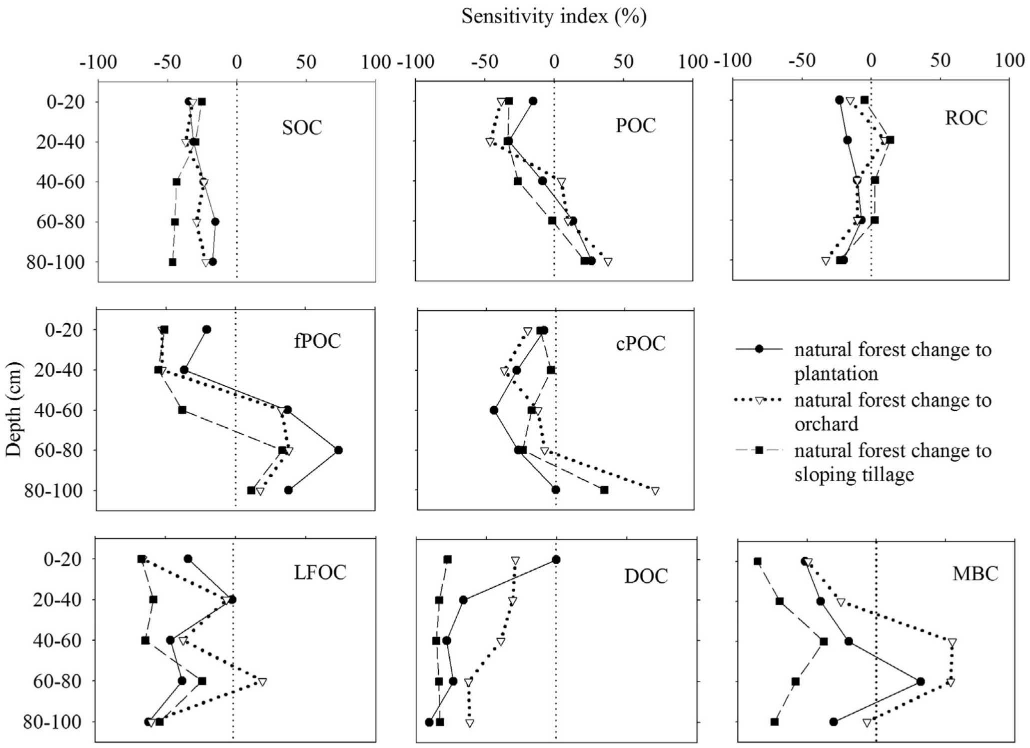

Fig. 3. Sensitivity index of LOC fractions in relation to subtropical land use changes across soil depth profiles. LOC, SOC, POC, ROC, fPOC, cPOC, LFOC, DOC, and MBC represent labile organic C, soil organic C, particulate organic C, readily oxidizable organic C, fine particulate organic C, coarse particulate organic C, light fraction organic C, dissolved organic C, and microbial biomass, respectively.

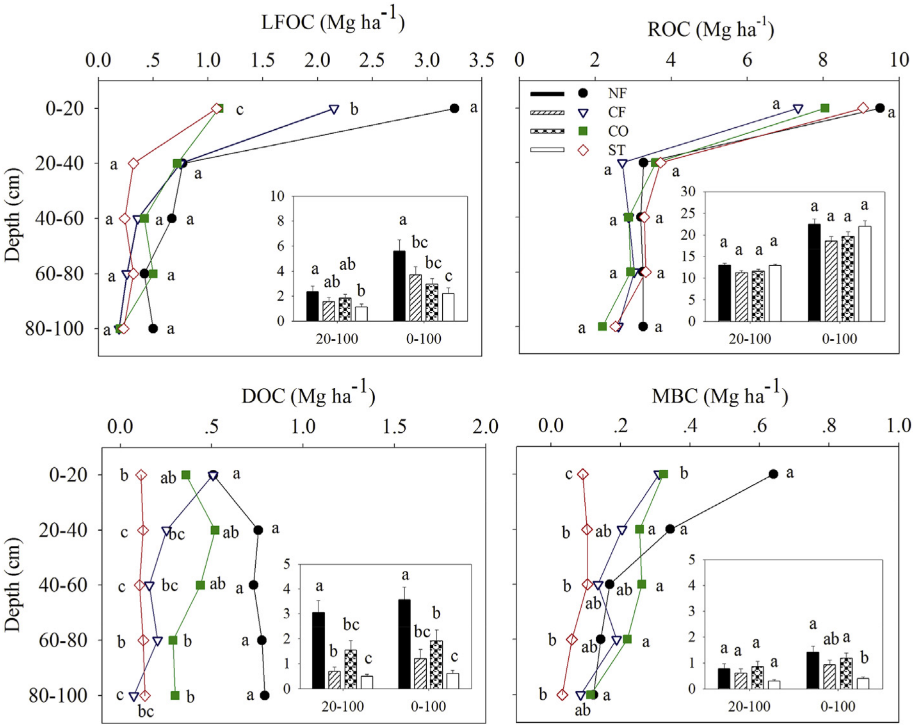

Fig. 4. LOC fraction stocks in relation to depth and land use systems in subtropical China. LOC, LFOC, ROC, DOC and MBC represent labile organic C, light fraction organic C, readily oxidizable organic C, dissolved organic C, and microbial biomass, respectively. Letters indicate significant differences among land use systems ($P < 0.05$).

was more pronounced in topsoil (49–86%) than in subsoil (21–61%) following land use change. DOC and MBC were the most sensitive indicators to land use change (Fig. 3). Noticeably, no significant reduction in MBC was observed in subsoil following the conversion from natural forest to orchard. This could be partially explained by the deep fine root distribution of Chinese chestnut (Fig. 1).

The stocks of SOC and its fractions (POC, LFOC and DOC) in subsoil showed a significant positive correlation ($R^2 > 0.94$) with fine root biomass present in the soil subsurface (20–60 cm) across all land use systems (Fig. 5). In addition, the stocks of LOC fractions tended to be positively linearly correlated with SOC stocks in subsoil (20–100 cm) (Fig. 6).

3.4. Proportions of LOC fractions to SOC

The proportion of the different LOC pools in relation to SOC can be used to detect changes in SOC quality. In the topsoil, the ratios fPOC, LFOC, and MBC to SOC decreased, while those of ROC and cPOC increased following land use change (Fig. 7). In subsoil, only the ratio of DOC to SOC decreased, the ratios POC, fPOC and ROC to SOC increased, and those of LFOC and MBC remained constant following land use change. In the topsoil, ratios fPOC, LFOC, DOC and MBC to SOC were more sensitive to conversion from natural forest to sloping tillage than SOC (Fig. 7).

4. Discussion

4.1. Organic C losses in top and subsoil following land use change

Land use change could dramatically affect the balance between soil C input and output, and consequently alter SOC content and composition regarding labile components. Land use change markedly reduced SOC and labile fractions both in topsoil (upper 20 cm) and subsoil (20–100 cm), which was consistent with our initial

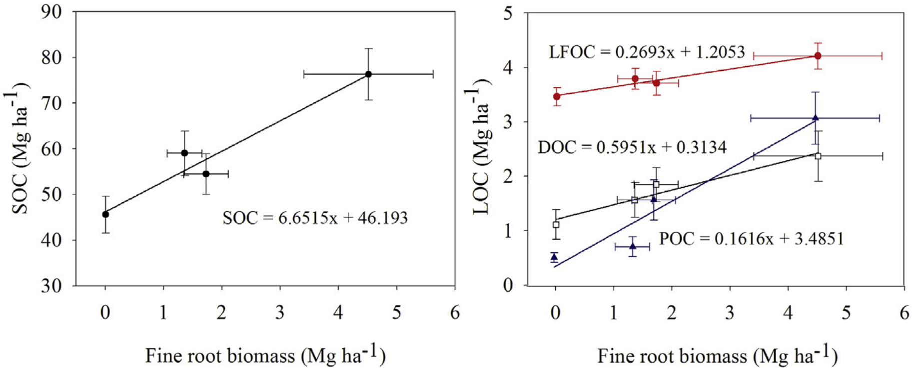

Fig. 5. Relation between SOC, LFOC (red), DOC (blue), and POC subsoil stocks (20–100 cm) and fine root biomass in 20–60 cm soil across land use systems in subtropical China. All regression lines are significant at $P < 0.05$, and R^2 values are above 0.94. SOC, POC, LFOC, and DOC represent soil organic C, particulate organic C, light fraction organic C, and dissolved organic C, respectively. Vertical and horizontal bars represent standard error for spatial variation (n = [3 plot]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

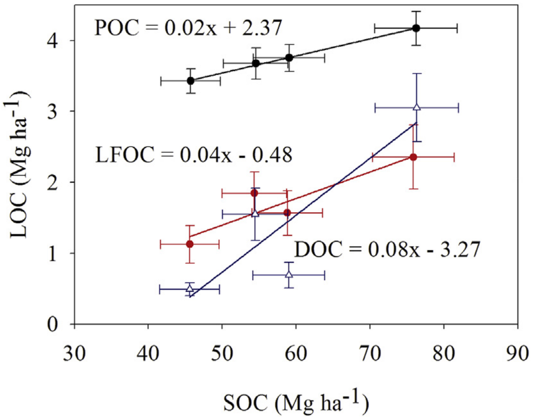

Fig. 6. Relation between POC, LFOC, and DOC (blue) stocks and SOC stocks in subsoil (20–100 cm) across land use systems in subtropical China. All regression lines are significant at $P < 0.1$, and R^2 values are above 0.80. POC, LFOC, DOC, and SOC represent particulate organic C, light fraction organic C, dissolved organic C, and soil organic C, respectively. Vertical and horizontal bars represent standard error for spatial variation (n = [3 plot]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

predictions. The depletion of SOC and labile components in topsoil observed after land use change was consistent with most previous observations in the tropics and subtropics (e.g. Deng et al., 2009; Don et al., 2011; Umrit et al., 2014). However, the direction and magnitude of SOC and labile fraction stocks in topsoil following land use change can significantly differ among biomes and geographical regions. For example, MBC content in topsoil increased, while SOC and other labile fractions (DOC and ROC) did not appear to be affected by the conversion of a subtropical natural forest to plantations even after three decades (Wang et al., 2013). This could be partly explained by the relative short duration of natural succession (50 years) for the referred natural forest. Different tree plantations could also differ in the quantity and quality of SOC input to the soil. In Malaysia, topsoil LOC content (0–15 cm) increased by 18% and 6% after forest conversion to oil palm plantations and pineapple orchards, respectively (Nahrawi et al., 2012). In Sergipe, Brazil, SOC content and active humic acid concentration in surface soil did not differ between a 12-year-old integrated coconut plantation and an adjacent remnant native Atlantic Forest (Guimarães et al., 2013). These observations could be related to the presence of leguminous cover crops, fertilization and management strategies for crop residues in the plantation.

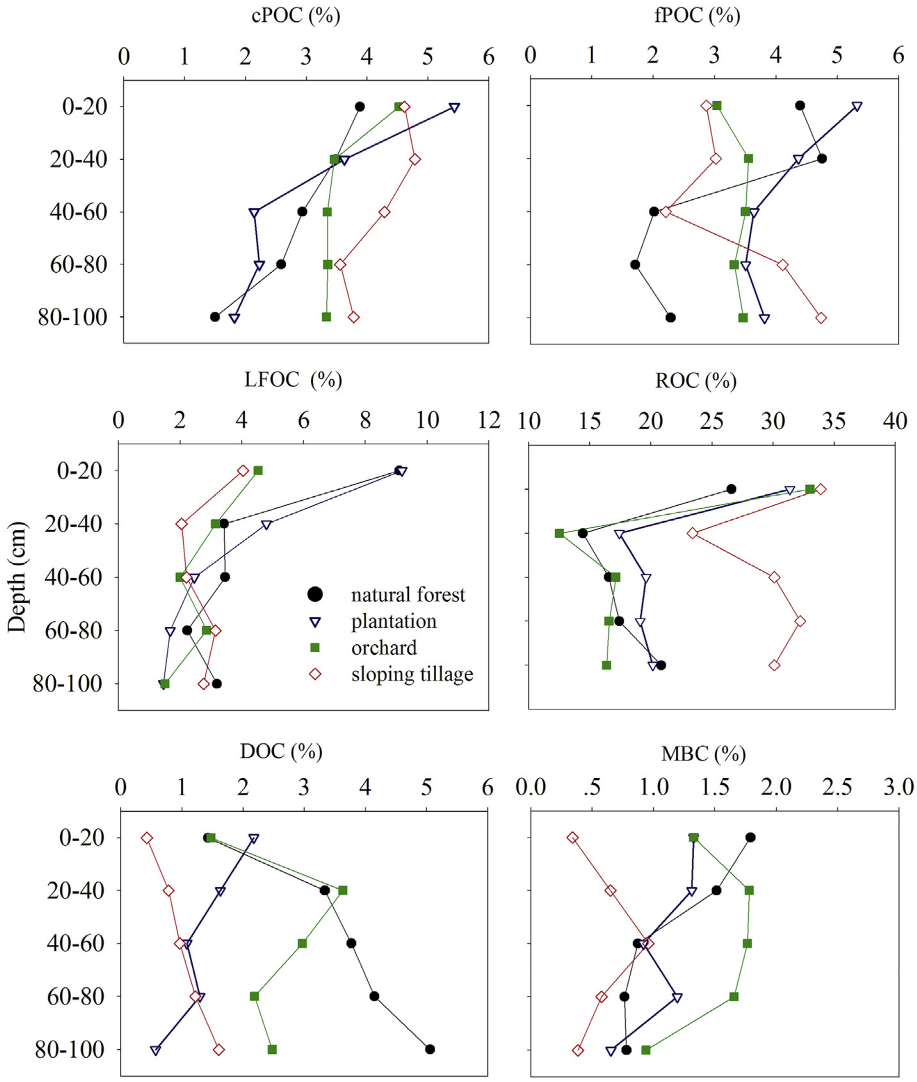

Fig. 7. Proportions of labile organic C fractions to soil organic C in relation to depth and land use systems in subtropical China. cPOC, fPOC, LFOC, ROC, DOC, and MBC represent coarse particulate organic C, fine particulate organic C, light fraction organic C, readily oxidizable organic C, dissolved organic C, and microbial biomass, respectively.

SOC and labile components also decreased in subsoil below 20 cm following land use change, highlighting that substantial stable SOC in subsoil could be mobilized and destabilized as a consequence of land conversion. At global and regional scales, change from forest to cropland also significantly reduced SOC content at 0–60 cm depth (Guo and Gifford, 2002; Don et al., 2011). To this end, we re-analyzed data from previous studies focused on issues other than the effect of land use change on subsoil SOC, and found that SOC stock in subsoil (20–100 cm) could be reduced by 26–61% after native forest conversion to secondary forests, plantations, and agricultural land in the tropics and subtropics (Pibumrung et al., 2008; Yang et al., 2009b). These values were similar to our results of 23–40% reduction in SOC stock in subsoil following land use change. SOC content also decreased by 63% and 73% in the first 0.2–0.5 m and 0.5–1 m of soil, respectively, following tropical forest conversion to sugarcane field (Deng et al., 2009). In the Amazon region, 20% or more of the C stock in subsoil found at 0.3–3 m depth could be mobilized by tropical forest clearing after 25 years of pasture growth (Veldkamp et al., 2003).

LFOC, POC and MBC stocks below 20 cm decreased after 16 years following the conversion of a subtropical old growth native forest to plantations (Yang et al., 2009a). In the Amazon plain, however, SOC stock below 10 cm depth is not affected by the conversion from lowland primary forest to agroforestry and monoculture plantations after 7 years (Schroth et al., 2002). This is probably thanks to the relatively flat terrain experiencing less severe soil erosion than the steep slopes considered in our study.

4.2. *Causes of organic C losses in subsoil following land use change*

Subsoil C stock depends on the delicate balance between C input and output. Following land use change, fresh C input to subsoil may be sharply reduced by the decline of soil and litter C stocks. In our study sites, plant species were altered, reducing and scattering plant cover, and a plant community dominated by deep-rooted trees and shrub species (Camphor) was replaced by shallow-rooted conifer trees (Chinese fir) and herbaceous vegetation (Fig. 1). These aboveground changes led to decrease in C input and C allocation in the subsoil linked to root turnover and rhizodeposition (Hafner et al., 2014). Stem density, basal area and fine root biomass also dramatically declined following natural forest conversion to plantation and orchard (Table 1). Fine root turnover decreased by 5–45% following a subtropical native forest conversion to plantations, and by 45% after tropical forest conversion to agroforest (Hertel et al., 2009; Sheng et al., 2010). Here, SOC stock and its fractions (POC, LFOC and DOC) in subsoil (20–100 cm) were significantly correlated with fine root biomass in subsurface soil (20–60 cm) across different land use systems (Fig. 5), showing that the decrease in subsoil C input (mainly through fine root biomass) were the dominant factors leading to the loss of SOC and labile components from subsoil after land use change.

Following land use change, litter and topsoil SOC stocks decreased by 47–99% and 25–35%, respectively (Table 1). In a previous study, we also found a decrease in fresh C input from plant litter by 32–63% following the conversion of a subtropical natural forest into plantations and orchards (Sheng et al., 2010). This process may also contribute to the reduction in subsoil C input (e.g., through leaching DOC, clay-combined C, etc.) from overlying topsoil and ground litter.

Organic C output might also be altered through land use change. In our previous study, the mean annual topsoil temperature increased by 7.8 °C after a subtropical natural forest was converted into sloping tillage, due to an increase in direct sunlight reaching the soil surface (Sheng et al., 2010). Increased soil temperatures can drive faster decomposition rates, including those of plant residues and topsoil SOC, leading to a reduced C input to the subsoil. In addition, decomposition rate in subsoil may be enhanced through targeted management practices (e.g., clear-cutting, burning, fertilization, irrigation, and deep plowing) (Wairiu and Lal, 2003). Furthermore, continuous cultivation in C-rich topsoil can supply fresh C input to subsoil (Chaopricha and Marín-Spiotta, 2014), which may enhance microbial decomposition of stable C in subsoil (Fontaine et al., 2007; Wang et al., 2014a; de Graff et al., 2014).

Soils exposed to harsh physical environments (e.g., those exposed to frequent heavy downpours, in steep slopes, or formed by loose soils) are often very vulnerable to surface erosion. Severe soil and water loss frequently occurred in the initial stage of land use change (van Noordwijk et al., 1997; Don et al., 2011). A large amount of fine, low-density and dissolved C in topsoil may be preferentially transported by runoff after young trees are renewed or planting of cash-crops. In the first 4 years after slash-and-burn, water-induced soil erosion, substantial soil (3740 kg ha^{-1}) and SOC (591 kg C ha^{-1}) loss in situ were observed in our study (Sheng et al., 2010). Thereafter, the low density A_h horizon disappeared, and the high density B_t horizon was closer to the surface (Table 1). Through soil erosion, subsoil C may also be destabilized through physical exposure at the surface and be open to O_2-rich air (Salomé et al., 2010). Additionally, fresh C input and mobilized nutrients may also stimulate C decomposition in the subsoil (Kautz et al., 2013). In subsoil, stocks of LOC fractions tended to be positively correlated with SOC stock (Fig. 6).

4.3. *Sensitive indicators of SOC alterations following land use change*

LOC fractions, determined through different fractionation approaches, are widely considered as early indicators of SOC response to short term land use change (Dungait et al., 2012). However, the sensitivity of LOC fractions to land use change depends on soil depth. In topsoil, fPOC, LFOC, DOC and MBC stocks were more sensitive to land use change than was SOC. In subsoil, on the other hand, only LFOC and DOC are sensitive enough to represent useful indicators of SOC changes. Similar to POC stocks and those of its different components, MBC in subsoil below 40 cm can increase after land conversion (Fig. 4), indicating that changes of LOC fractions may follow opposite patterns to those in topsoil. In another example, soil C accumulation was almost entirely from LFOC in topsoil (0–7.5 cm), and C loss was mainly from C fractions associated with silt and clay-size particles in the subsoil (35–60 cm) 48 years after the conversion of old fields into secondary forest (Mobley et al., 2015). Consequently, the effects of land use change on LOC fractions observed in the topsoil may not directly affect the subsoil.

The response of LOC fractions to land conversion also depends on the type of land use change. The insensitive response of ROC stocks to land use changes observed in this study, partly due to there being a large proportion of passive SOC, is consistent with several previous studies (Mendham et al., 2002; Tirol-Padre and Ladha, 2004). In addition, the $KMnO_4$ oxidation method was very sensitive to the presence of lignin or lignin-like compounds and therefore to the nature of the vegetation present, which may also explain the insensitivity of ROC to land use change (Skjemstad et al., 2006). POC stock can not be used either as a sensitive indicator of SOC change because it is masked by the insensitive response of the cPOC component (Fig. 4). Although fPOC is relatively recalcitrant and more stable than cPOC (Jolivet et al., 2003), it consists of finer particles, and therefore, it can be easily translocated downwards by preferential flow through soil pores and cracks between aggregates.

Following land use change, the reduced proportions of POC, LFOC, DOC, and MBC to SOC indicated a reduction in the proportion of readily available substrates and a lower SOC quality (Yang et al., 2009b). These results further imply that these four ratios can be considered as active indicators to detect alterations in SOC quality due to land use change (Fig. 7). Furthermore, the decreased DOC to SOC ratio in subsoil following land use change showed that the main DOC loss occurred in the subsoil, highlighting the importance of DOC sorption in the subsoil. Similarly, land use and fertilization practices induced changes in the DOC to SOC ratio, which were even higher in subsoil than in topsoil (Zhang et al., 2006; Liang et al., 2012). The increased ratios of POC, cPOC and fPOC to SOC in subsoil may also be largely associated with DOC leaching.

5. Conclusions

The sites selected in this study were representative of the most common land use changes occurring in subtropical China. SOC stocks and those of the labile fractions decreased in topsoil and subsoil below 20 cm following land conversion. The LOC fractions to SOC ratios also decreased, indicating a reduction in C quality as a consequence of land use change. Reduced LOC fraction stocks in subsoil could partially be explained by the decrease in fine root biomass in subsoil, with consequences for SOC stock. However, not all labile fractions could be useful early indicators of SOC alterations due to land use change. In fact, only fPOC, LFOC, and MBC in topsoil, and LFOC and DOC in subsoil were highly sensitive to land use change in subtropical China. We conclude that land use changes can influence both top and subsoil, consequently leading to decrease in C sequestration over long term. Therefore, long-term effects of land use on SOC stocks should be considered at soil depths greater than 20 cm.

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