Continuous Maize Cropping Accelerates Loss of Soil Organic Matter in Northern Thailand as Revealed by Natural 13C Abundance

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Continuous maize cropping accelerates loss of soil organic matter in northern Thailand as revealed by natural ^{13}C abundance

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Running title: Cultivation effects on soil carbon stocks

Keywords: carbon sequestration; density fractionation; conventional tillage; shifting cultivation; soil organic matter

Abstract

Aims: The loss of soil organic matter (SOM) has widely been reported in the tropics after changing land use from shifting cultivation to continuous cropping. We tested whether continuous maize cultivation accelerates SOM loss compared to upland rice and forest fallow.

Methods: Because litter sources include C4 plants (maize in maize fields and *Imperata* grass in upland rice fields) in Thailand, C3-derived and C4-derived SOM can be traced using the differences in natural ^{13}C abundance ($\delta^{13}C$) between C3 and C4 plants. We analyzed the effects of land use history (cultivation or forest fallow period) on C stocks in the surface soil. Soil C stocks decreased with the cultivation period in both upland rice and maize fields.

Results: The rate of soil organic carbon loss was higher in maize fields than in upland rice fields. The decomposition rate constant (first order kinetics) of C3-plant-derived SOM was higher in the maize fields than in the upland rice fields and the C4-plant-derived SOM in the forest fallow. Soil surface exposure and low input of root-derived C in the maize fields are considered to accelerate SOM loss. Soil C stocks increased with the forest fallow period, consistent with the slow decomposition of C4-plant-derived SOM in the forest fallows.

Conclusions: Continuous maize cultivation accelerates SOM loss, while forest fallow and upland rice cultivation could mitigate the SOM loss caused by continuous maize cultivation.

Introduction

In Southeast Asia, traditional shifting cultivation has been replaced by continuous cropping systems (Kyuma and Pairintra, 1983). In northern Thailand, upland rice is cultivated between forest fallow periods for subsistence, but continuous maize cultivation has increased along paved roads with infrastructure improvement (Bruun et al., 2017). Intensive agriculture without organic amendment leads to a loss of soil organic matter (SOM), which is essential for increasing plant productivity and mitigating soil acidification (Kimetu et al., 2008; Fujii et al., 2009; Jaiarree et al., 2011).

The intensification of agriculture, including tillage, generally risks increasing microbial decomposition activities and soil erosion (Kimetu et al., 2008), but the impact could vary with crop plants. Upland rice develops larger root systems than maize, especially under nitrogen and water stress (Kondo et al., 2000). Because root litter is less decomposable than leaf litter (Fujii et al., 2019), the lower shoot/root ratios of upland rice could provide greater root-derived C input than maize of the same biomass (Kondo et al., 2000). In maize fields, the low root-derived C input could limit the supply of SOM precursors, despite the high primary productivity (Carvalho et al., 2017). Global assessment also suggests lower SOM stocks in maize fields compared to other crops (West et al., 2002). We hypothesized that continuous maize cultivation results in greater SOC loss compared to forest fallow or upland rice cultivation.

Because SOM gain or loss is dependent on the balance between C inputs (mainly litter inputs) and outputs (heterotrophic respiration, leaching, and erosion), the effects of land use on SOM stocks can be quantified using annual soil C budgets (Fujii et al., 2009) or long-term monitoring of soil organic carbon (SOC) stocks (Fujii et al., 2019, 2020). Alternatively, SOC stocks can be compared between sites that share soil attributes with different land-use histories (cultivation or fallow periods). Although our study site is in a remote part of northern Thailand, its land-use history has been monitored continuously (Sakai, 2005; Fig. 1), enabling us to compare the effects of land-use change on SOC stocks.

Continuous maize cropping results in a loss of forest-derived SOM and a gain of maize-derived SOM. Because maize (C4 plant) and most woody species (C3 plants) have different natural ^{13}C abundances ($\delta^{13}C$) due to their different photosynthetic pathways (Yoneyama et al., 2006), C3-derived and C4-derived SOM can be traced in maize fields. In addition, while upland rice is a C3 plant, the dominant weed (*Imperata cylindrica*) of upland rice fields is a C4 plant. This allows us to trace the dynamics of C3- and C4-derived SOM under different fallow and rice cultivation periods in northern Thailand. To test the hypothesis that continuous maize cultivation results in greater SOC stock loss than forest fallow or upland rice cultivation, we compared the SOM dynamics of forest fallow, upland rice, and maize fields.

Materials and Methods

Sampling soil material

Soils were collected in 2014 in Ban Rakpaendin, Chiang Rai Province (19° 50' N, 100° 20' E; 697 m a. s. l.), where the mean annual air temperature is 25.0°C and the precipitation is 2084 mm yr^{-1}. The forest and forest fallow vegetation were dominated by *Lithocarpus* and *Eugenia* spp., with some planted rubber (*Hevea brasiliensis*) and orange (*Citrus reticulata*) trees. The soils were clayey and classified as Typic Haplustults (Table 1; Soil Survey Staff, 2014). The village land use has been affected by socio-economic development and political instability in Indochina. Before the Indochina War, the *Mieng* (a hill tribe) conducted shifting cultivation of upland rice (Sakai, 2005). After the war, northern Thai (*Khon Muang*) and *Hmong* migrated in 1982 and 1987, respectively, and started cultivating upland rice and maize in the upstream forest (Fig. 1a). After the village protected the upstream forest for water security and a paved highway was constructed in 1995, intensive maize cultivation expanded to the fields close to the highway (Fig. 1a,b). The population increase and influx of refugees increased maize production. The land use history has been recorded in the village (Fig. 1a,b). The cultivation and fallow periods of the sampling locations were determined by interviews with farmers and a field survey, cross-checked using satellite photos (1992, 2002, 2007, 2014) and a land use map (Sakai et al., 2005; Fig. 1b).

Calculating the contributions of C3- and C4-plant-derived carbon

The physical fractionation of soil is useful for tracing the pools of labile (free) and stable (mineral-associated) SOM in the light and heavy fractions, respectively (Hassink, 1995; Tan et al., 2007). The SOC in the two fractions was determined as follows. Briefly, 10 g of air-dried soil was dispersed in a sodium iodide (NaI) solution (1.60 g cm^{-3}), centrifuged at 2600 *g* (modified from Spycher et al., 1983), and the light (< 1.60 g cm^{-3}) and heavy (> 1.60 g cm^{-3}) fractions were recovered. The total C and N concentrations in soils were measured using a CN analyzer (Vario Max CN; Elementar Analysensysteme, Langenselbold, Germany).

Because the surface soil horizon is most sensitive to land use change in a soil profile (Tan et al., 2007), this study focused on the C stocks in the top 0–5 cm of soil, which were calculated as follows:

$$Soil\ C\ stock\ (0\text{–}5\ \mathrm{cm}) = Soil\ C \times 0.05 \times 100 \times 100 \times Bulk\ density/1000 \quad \text{(Eq. 1)}$$

where the soil C stock (0–5 cm) (Mg C ha^{-1}), soil C concentration in the light and heavy fractions (g C kg^{-1}), surface 0–5-cm soil volume (m^{-3}) (= 0.05 m × 100 m × 100 m), and bulk density (Mg m^{-3}) were measured using three replicates of a 0.1-L core per plot.

The contributions of C3- and C4-plant-derived SOM to soil C were estimated using the measured C-isotope signatures (δ^{13}C) and a mass balance approach (Nguyen-Sy et al., 2020). A sample (~50 μg C) was weighed in a tin capsule and the $\delta^{13}C$ isotope composition was measured for the litter and soil samples using an online C analyzer (NC 2500; Thermo Fisher Scientific, Waltham, MA, USA), coupled with an isotope ratio mass spectrometer (MAT252; Thermo Electron, Bremen, Germany). All $\delta^{13}C$ values are expressed relative to the international standard Vienna Pee Dee Belemnite (VPDB): $\delta^{13}C = (R_{sample}/R_{VPDB} - 1)$. The standard deviation for four replicate combustions of the same standard within a sequence was less than 0.10‰.

The sample $\delta^{13}C$ values depend on the mixture of C3 plant-derived C and C4-plant-derived C, as expressed in the following equation (Nguyen-Sy et al., 2020):

$$\delta^{13}C(Sample) = x \times \delta^{13}C(C3) + (1 - x) \times \delta^{13}C(C4) \qquad \text{(Eq. 2)}$$

where $\delta^{13}C$ (sample) is the measured $\delta^{13}C$ value of the sample, $\delta^{13}C$ (C3) is derived from the C3-plant-derived C (av. −28.6‰), $\delta^{13}C$ (C4) is derived from the C4-plant-derived C (av. −12.5‰), and x denotes the proportion of C3-plant-derived C. The proportions of C3-plant-derived C (x) and C4-plant-derived C ($1 - x$) were estimated with the following equations:

$$Proportion\ of\ C3\ derived\ C = \frac{\delta^{13}C(Sample) - \delta^{13}C(C4)}{\delta^{13}C(C3) - \delta^{13}C(C4)} \qquad \text{(Eq. 3)}$$

$$Proportion\ of\ C4\ derived\ C = 1 - \frac{\delta^{13}C(Sample) - \delta^{13}C(C4)}{\delta^{13}C(C3) - \delta^{13}C(C4)} \qquad \text{(Eq. 4)}$$

The SOM loss data were fitted to a single exponential decay function:

$$R_r/R_i = e^{-kt} \qquad \text{(Eq. 5)}$$

where R_r and R_i are the initial and remaining C stock (Mg C ha^{-1}) respectively, k is the decomposition rate constant (yr^{-1}), and t is the cultivation or fallow period (yr).

Statistics

All results are expressed on an oven-dried weight basis for soil samples (105°C, 24 h) and plant samples (70°C, 48 h). Significant ($P < 0.05$) differences between the light and heavy fractions or between land-use types in the soil C stocks, $\delta^{13}C$ values, and decomposition rate constants (k) were tested using analysis of variance (ANOVA). The SOM loss data were fitted to Eq. 5 using the least-squares technique. The differences in the slopes of the linear regression equations of SOM loss were compared between land-use types. All statistics were performed using SigmaPlot 14.5 and tested at a significance level of 0.05, unless otherwise stated.

Results

Characteristics of the litter and soil density fractions

Soil C stocks were positively correlated with the forest fallow period (Fig. 2a). The annual gain of 0.84 Mg C ha^{-1} yr^{-1} in soil corresponded to 16.2% of the annual litterfall C input in the forest fallow (Table 1; Fig. 2a). By contrast, the soil C stocks were negatively correlated with the cultivation period in both the upland rice and maize fields (Fig. 2b,c). Comparison of the slopes of the linear regressions indicated that the SOC loss rate was significantly ($P < 0.05$) higher in the maize field than in the upland rice field (Fig. 2bc).

The $\delta^{13}C$ values of *Imperata* grass and maize litter (C4 plants) differed significantly from those of forest litter (C3 plants) (Table 1). This supports the precondition of our study that C3 plant-derived and C4 plant-derived SOM can be traced in soils. The C/N ratios and C concentrations were significantly ($P < 0.05$) lower in the heavy fractions than in the light fractions (Table 2). The $\delta^{13}C$ values in the heavy fraction were significantly ($P < 0.05$) higher than in the light fraction in the forest soils, but no significant differences in the $\delta^{13}C$ values were found between the heavy and light fractions in the upland rice and maize fields (Table 2).

Contribution of C3- or C4-plant-derived carbon to soil organic matter

In both the upland rice and maize fields, the $\delta^{13}C$ values in the light and heavy fractions were positively correlated with cultivation period (Fig. 3a,b). By contrast, the $\delta^{13}C$ values in the light and heavy fractions of the forest sites were negatively correlated with the fallow period (Fig. 3a,b). C3-plant-derived C was dominant at all sites, but the respective proportions of C3-plant-derived C decreased to 62% and 67% in the light and heavy fractions of the cropland soils. The proportion of C4-plant-derived C in the light fractions increased from 10% to 38% in the maize fields and from 8% to 24% in the upland rice field (Table 2). Similarly, the proportion of C4-

plant-derived C in the heavy fractions increased from 3% to 33% in the maize fields and from 11% to 32% in the upland rice field (Table 2). The C3-plant-derived C stock decreased with cultivation period in the maize (Fig. 4a) and upland rice (Fig. 5a) fields. However, the proportion of C4-plant-derived C in the heavy fraction decreased from 30% to 6% in the forest fallow (Table 2). The total C stock in the soil increased with the fallow period in the forest fallows, but the C4-plant-derived C stocks decreased (Fig. 5b).

Fitting the SOM loss data to an exponential decay gives the decomposition rate constants or k values, except for the light fraction of the forest sites (Table 3; Figs. 4a, 5a,b). The k value of the heavy fraction was significantly ($P < 0.05$) lower than that of the bulk soil in the forest fallow sites (Table 3). By comparison, the k value of the heavy fraction was significantly ($P < 0.05$) higher than that of light fraction in both the upland rice and maize fields (Table 3). The k values of SOM decomposition in the bulk soil were in the order of maize field (0.044) > upland rice field (0.031) > forest (0.020) (Table 3).

Discussion

Effects of tillage on soil organic matter decomposability in different density fractions

SOM in the light fraction generally decomposes faster than SOM associated with minerals in the heavy fraction (Hassink, 1995; Tan et al., 2007). Our study also showed that the C4-plant-derived SOM in the light fraction of forest fallow soils also decomposes faster than in the heavy fraction (Table 3). The SOM in the heavy fraction has higher $\delta^{13}C$ values and lower C/N ratios due to selective respiration of ^{12}C relative to ^{13}C (Table 2) and the higher degree of humification, compared to the light fraction (Table 2; Wagai et al., 2020).

In the maize field, C3-plant-derived C in the heavy fraction decomposes faster than in the light fraction (Table 3). This contrasts with reports that recalcitrant SOM in the heavy fraction decomposes slowly (Hassink, 1995; Tan et al., 2007), but faster turnover of the heavy fraction has also been reported (Crow et al., 2007). SOM turnover could vary, depending on soil types and tillage practices (Gregorich et al., 1995; Sollins et al., 2009). Tillage and input of accessible labile litter could stimulate microbial activity to decompose the humified SOM (priming effects) in the heavy fraction for nutrient mining (Dimassi et al., 2014). Note that C3-plant-derived SOM is not equal to forest-derived SOM in the maize fields, as C3 plant litter inputs from weeds (e.g., Asteroideae spp.) could be supplied to C3-derived SOM in the maize fields. This induces risk of underestimating the decomposition rate constants of the light fraction.

Effects of land-use types on soil carbon stocks

We hypothesized that continuous maize cultivation results in greater loss of SOC stocks compared to forest fallow or upland rice cultivation. This is supported by the higher SOC loss rate in the maize field than in the upland rice field (Fig. 2b,c) as well as higher rate constants of C3-plant-derived SOM decomposition in the maize fields compared to C3-plant-derived SOM decomposition in the upland rice fields and C3-plant-derived SOM decomposition in the forest fallows (Table 3; Figs. 4, 5). This is consistent with a net C loss in the annual C balance between litter inputs and heterotrophic respiration (Fujii et al., 2009) as well as a global assessment reporting lower soil C stocks in maize fields compared to other crops (West et al., 2002).

The slower decomposition of C3-plant-derived SOM in the upland rice fields compared to the maize fields (Table 3) is consistent with the lower SOM loss rates in upland rice fields (Fig. 2b). As in the maize field, C3-plant-derived SOM is not equal to forest-derived SOM in the upland rice fields, as upland rice-derived SOM could also be provided. Based on the lower shoot/root ratios of upland rice, root-derived C inputs would be greater in the upland rice fields than in the maize fields (Kondo et al., 2000). This could mitigate the loss of C3-plant-derived SOM in the upland rice fields (Fig. 5a). The limited erosion due to rice straw covering the soil surface could also mitigate SOM loss.

The main source of C4-plant-derived SOM in the forest fallow is *Imperata* grass, as upland rice was traditionally cultivated before forest fallow started (Sakai, 2005). SOM of C4 plant origin can decompose faster than SOM of C3 plant origin (Wynn and Bird, 2007). However, the decomposition of C4-plant-derived SOM in the forest fallow is much slower than the decomposition of C3-plant-derived SOM in the croplands in our study (Table 3). Potential reasons for the preservation of C4-plant-derived SOM in forest fallow are aggregate formation under no tillage, less erosion, and soil acidity (Gregorich et al., 1995; Fujii et al., 2019). As seen in the lower decomposition rate constants of the heavy fraction (Table 3), no tillage practice under forest fallow vegetation favors the development of aggregates and physical protection of SOM in aggregates (Tan et al., 2007; Wagai et al., 2020). In addition, the forest canopy can limit erosion by rainfall and temperature rise by sunlight (Pimentel and Kounang, 1998). Acidic soil limits cellulose decomposition in forest litters (Hayakawa et al., 2014; Fujii et al., 2019).

Implications for sustainable soil management

SOM gain or loss is directly related to the C sink/source function of soil and indirectly affects sustainable maize productivity via effects on soil acidity, because maize growth is sensitive to acidity (Calba et al., 2006; Minasny et al., 2017). Soil pH increased with the C concentration in the heavy fraction of cropland soil (Fig. S1). SOM has two functions in pH control—pH buffering due to the weak acid nature of functional groups and consumption of protons via the net mineralization of organic anions (Poss et al., 1995; Fujii et al., 2012). Soil acidification under continuous cropping can be mitigated by the mineralization of SOM that has accumulated under the forest fallow (Fujii et al., 2009, 2021). Therefore, a gain or loss of SOM leads to a respective gain or loss of soil potential to neutralize acidity. The annual gain of 0.12 Mg C ha^{-1} yr^{-1} in cropland soils corresponded to only 2.8% of the annual maize residue C input (Table 1; Figs. 4c, Fig. S2c) compared to 16.2% of the annual litterfall C input in the forest fallow soils (Table 1; Fig. 2a). Judging from the finding that soil C accumulation rates in the forest fallow exceed SOM loss rates in the cropland soils (Fig. 2), forest fallow has high potential to mitigate soil degradation. When we compare upland rice and maize, upland rice has slower rates of SOM loss despite a similar gain rate of C4-plant-derived C in soil (Figs. 2b,c, Fig. S2c). Upland rice cultivation and forest fallow both involve low soil disturbance, which favors the development of soil aggregates and mitigation of erosion (Pimentel and Kounang, 1998). These SOM preservation mechanisms should be applied to develop a land-use strategy to mitigate soil degradation, such as agroforestry involving crop and rubber or orange trees.

Conclusions

We showed quantitatively that continuous cropping of maize or upland rice leads to a loss of SOC. Especially, continuous cropping causes a greater loss of SOC compared to upland rice cultivation. The decomposition of C4-plant-derived SOM was slower in forest fallow than the decomposition of C3-plant-derived SOM in maize or upland rice fields. Since the soil C stocks increased with the forest fallow period and upland rice cultivation has a slower loss of SOC, the inclusion of forest fallow and upland rice cultivation in a land-use strategy is optimal for maintaining SOC stocks.

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Conflict of Interest: The authors declare that they have no conflict of interest

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Table captions

Table 1 Site information of litter and soil

Table 2 Soil C stocks and ^{13}C natural abundance in light and heavy fractions

Table 3 Decomposition rate constants of C3 or C4 plant-derived organic matter in the light and heavy fractions

Figure captions

Fig. 1 (a) Land use change from shifting cultivation in the upstream area to continuous cropping in the downstream area close to highway, (b) land use map in 1992 and 2004, and (c) sampling locations on topographic map (contours with 50m interval). Data source was Sakai (2005).

Fig. 2 Changes in soil carbon stocks (0-5 cm) of (a) forest fallow, (b) upland rice field, and (c) maize field.

Fig. 3 Changes in soil $\delta^{13}C$ values of (a) light fraction and (b) heavy fraction of the surface soil (b).

Fig. 4 Changes in stocks (0-5 cm) of (a) C3-plant-derived C (bulk soil), (b) C3-plant-derived C in the light and heavy fractions, (c) C4-plant-derived C (bulk soil), and (d) C4-plant-derived C in the light and heavy fractions in the maize fields. The curves represent fitting with single exponential decay function, while lines represent fitting with single linear regression.

Fig. 5 Changes in stocks (0-5 cm) of (a) C4-plant-derived C (bulk soil) in the forest fallows and (b) C3-plant-derived C (bulk soil) in the upland rice fields. The curves represent fitting with single exponential decay function.

Fig. S1 Relationship between soil pH and soil C concentration in the heavy fraction (> 1.60 g cm^{-3}).

Fig. S2 Changes in stocks (0-5 cm) of (a) forest-derived C (bulk soil), (b) forest-derived C in the light and heavy fractions, (c) C4-plant-derived C (bulk soil), and (d) C4-plant-derived C in the light and heavy fractions in the upland rice fields. The curves represent fitting with single exponential decay function, while lines represent fitting with single linear regression.

Figures

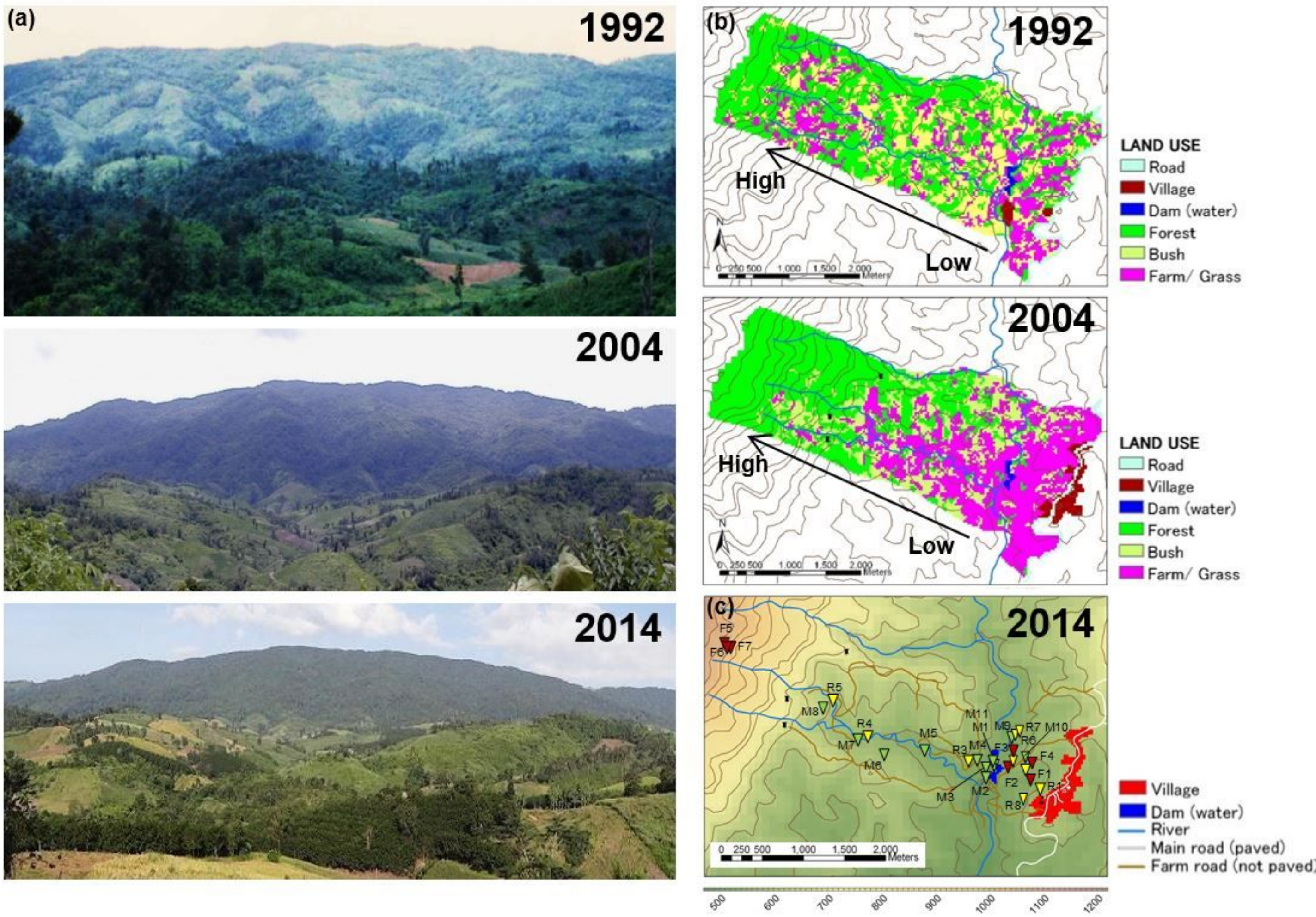

Figure 1

(a) Land use change from shifting cultivation in the upstream area to continuous cropping in the downstream area close to highway, (b) land use map in 1992 and 2004, and (c) sampling locations on topographic map (contours with 50m interval). Data source was Sakai (2005).

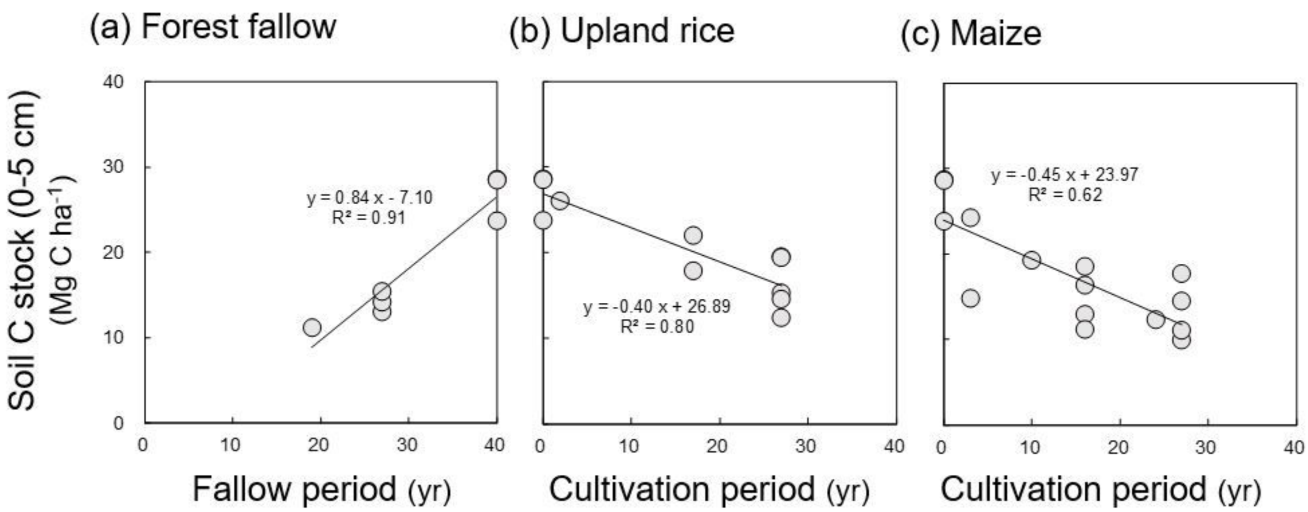

Figure 2

Changes in soil carbon stocks (0-5 cm) of (a) forest fallow, (b) upland rice field, and (c) maize field.

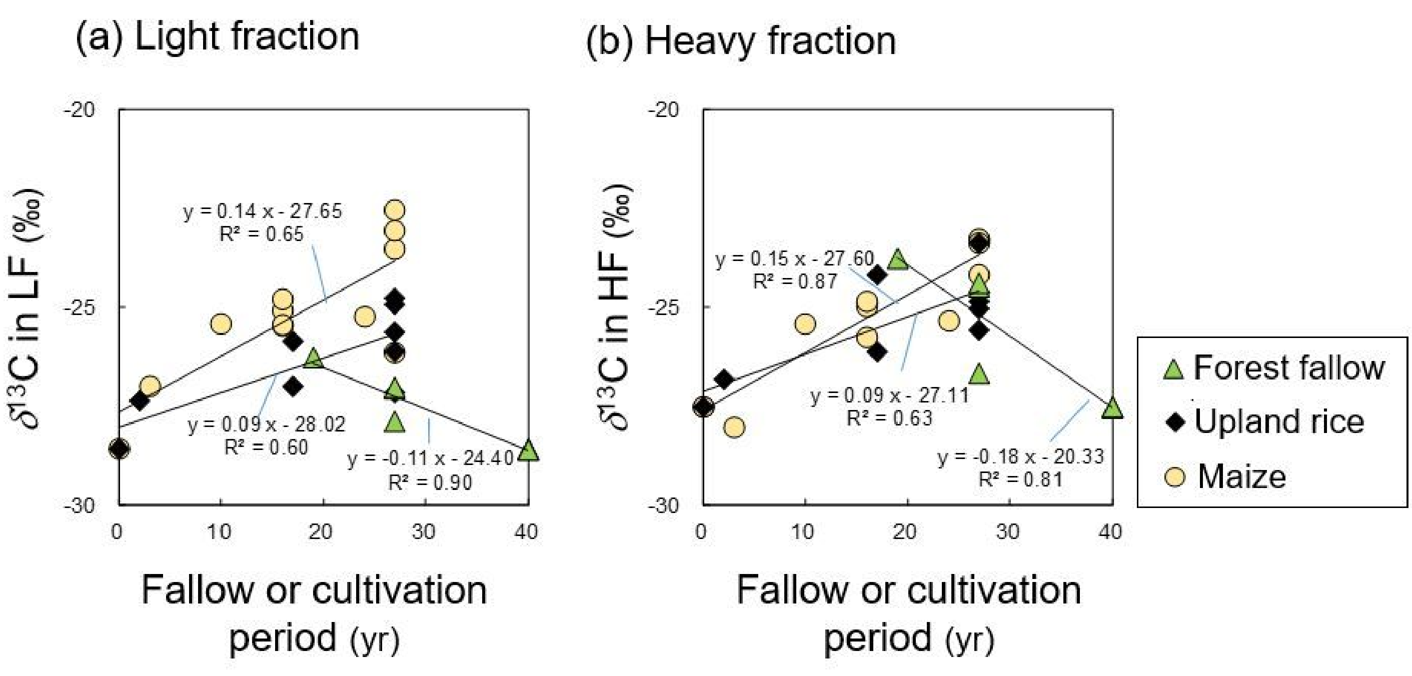

Figure 3

Changes in soil d^{13}C values of (a) light fraction and (b) heavy fraction of the surface soil (b).

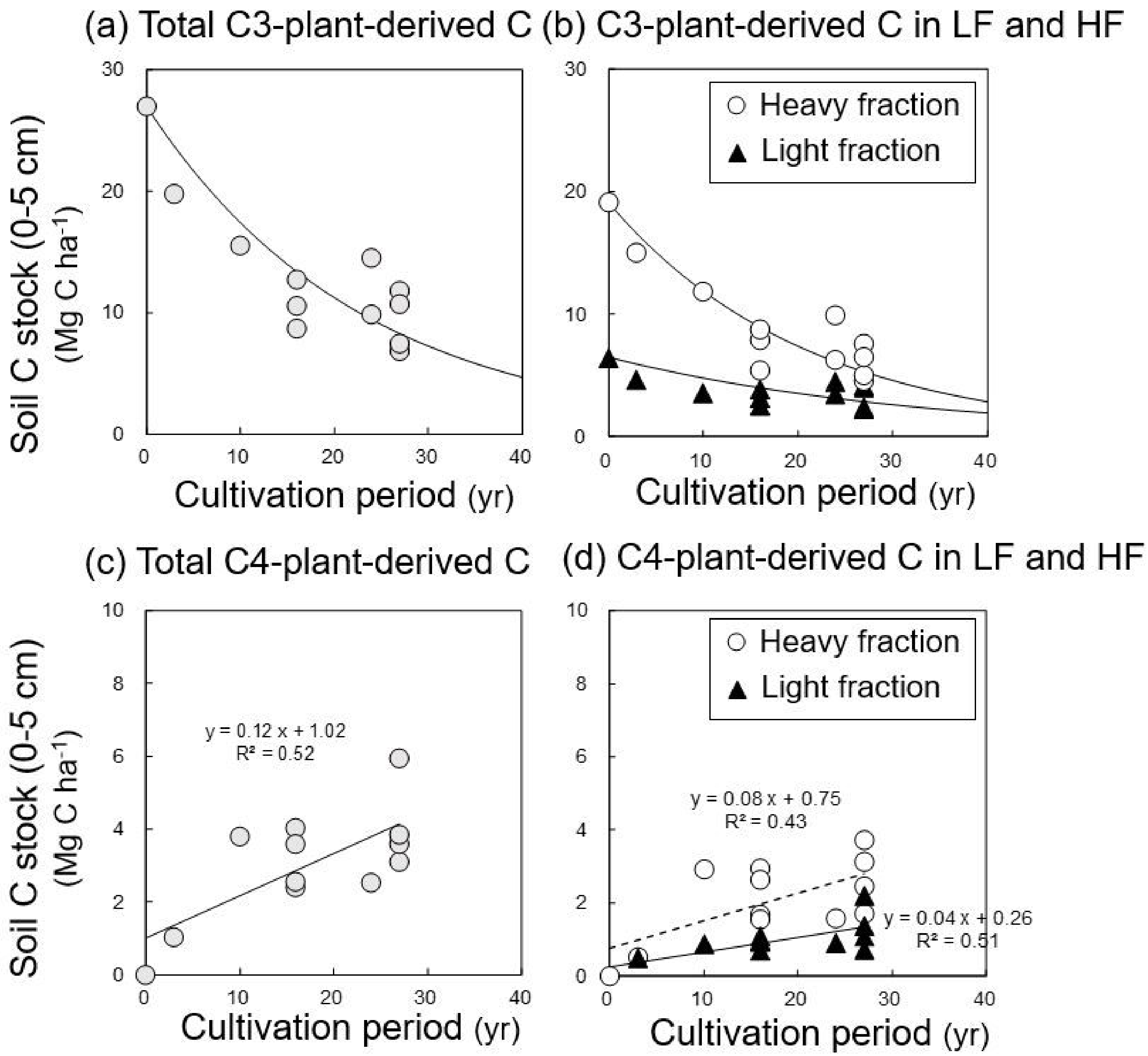

Figure 4

Changes in stocks (0-5 cm) of (a) C3-plant-derived C (bulk soil), (b) C3-plant-derived C in the light and heavy fractions, (c) C4-plant-derived C (bulk soil), and (d) C4-plant-derived C in the light and heavy fractions in the maize fields. The curves represent fitting with single exponential decay function, while lines represent fitting with single linear regression.

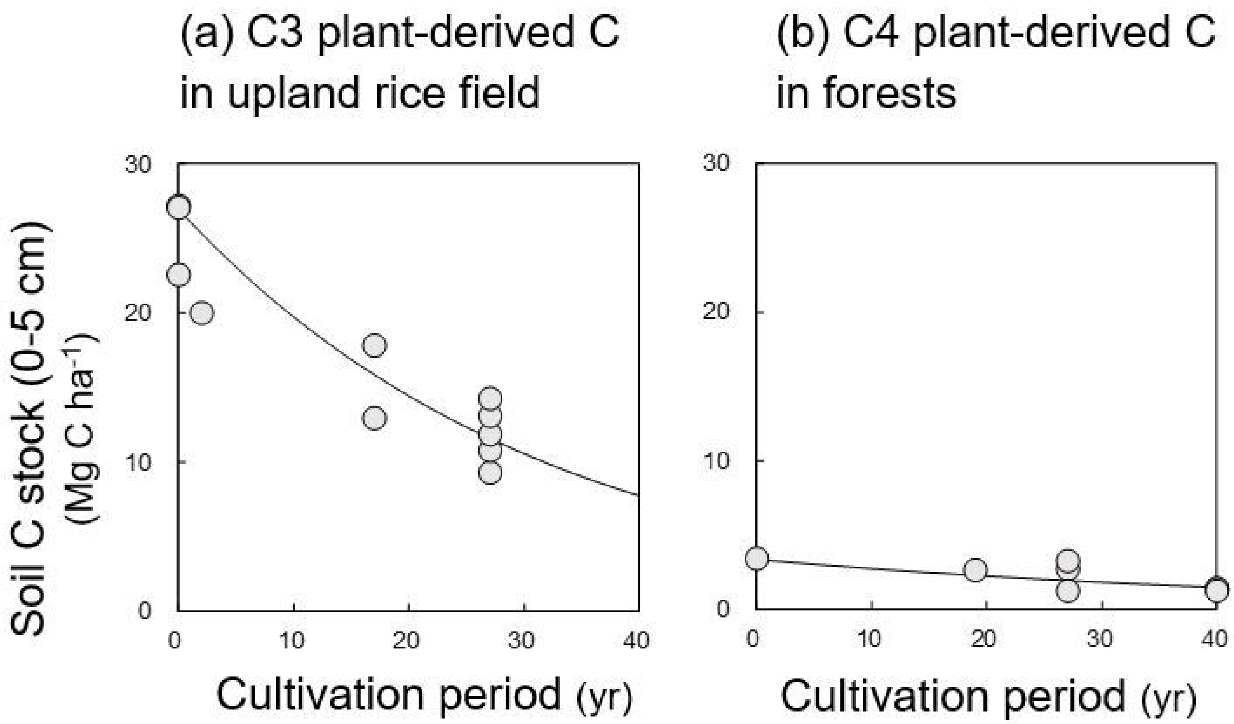

Figure 5

Changes in stocks (0-5 cm) of (a) C4-plant-derived C (bulk soil) in the forest fallows and (b) C3-plant-derived C (bulk soil) in the upland rice fields. The curves represent fitting with single exponential decay function.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.pptx
- s1.jpg
- s2.jpg