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Effects on soil chemistry of tropical deforestation for agriculture and subsequent reforestation with special reference to changes in carbon and nitrogen

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ABSTRACT

While soils can act either as a source or as a sink for atmospheric carbon dioxide and nitrogen, depending on land cover change and management, there is a great need to improve our understanding of the dynamics of soil structure and chemistry following land conversion in tropical regions. In this study, we investigated various soil structural and chemical variables (bulk density, pH, cation exchange capacity, phosphorus, magnesium, potassium), soil carbon (C), soil nitrogen (N), $\delta^{13}C$, and $\delta^{15}N$ in relation to conversion of rain forest to tea cultivation and subsequent changes due to agricultural abandonment and reforestation with Caribbean pine. Although Caribbean pine has shown potential for reforestation throughout Asia and Latin America, effects on soil properties in comparison with other land uses have not been quantified. Our study compared: (1) the original mixed-dipterocarp rain forest, (2) tea plantations, (3) Kekilla fernlands and (4) Caribbean pine plantations. Tea plantations show higher bulk density (BD) as an evidence of compaction. Although soil C concentration in tea plantations were lower than other land uses at 0–10 cm, when bulk density was used with C as a composite measure, tea plantation showed the highest value for both soil C and N stocks. Disregarding tea plantations, Caribbean pine plantations had the highest C but showed the lowest N stocks at both soil depths. Soil $\delta^{13}C$ and $\delta^{15}N$ values of all land uses increase with increasing soil depth; but Caribbean pine plantations showed the greatest increase in $\delta^{13}C$ at both soil depths (e.g. $-27.82 \pm 0.38‰$ at 0–10 cm to $-26.50 \pm 0.37‰$ at 10–20 cm). For both Kekilla fernlands and Caribbean pine plantations the relationship between $\delta^{13}C$ and $\delta^{15}N$ was strongly linear. By comparing the physical and chemical soil properties of these land uses with undisturbed rain forest, we established baseline data to determine influence of land conversion on soil properties. Based on soil pH, CEC and other major nutrients (P, K, Mg), there are strong legacy effects of land use potentially from both fertilization and fire. Our results also showed strong evidence that $\delta^{13}C$ and $\delta^{15}N$ was both increased with depth under pine reforestation and fernlands, suggesting soils can recuperate with a consistent input of litter and slower decomposition processes. There is some evidence that recruitment of natural regeneration beneath pine can help facilitate faster litter decomposition that can revert soil structure and fertility to a status similar to that of the original forest.

1. Introduction

Land use and land use change in the tropics is considered the second largest cause of anthropogenic greenhouse gas emissions after fossil fuel combustion (van der Werf et al., 2009; Don et al., 2011; Pan et al., 2011). Much research has been done to reduce uncertainty in quantifying above-ground terrestrial carbon (C) (Sitch et al., 2003; Heimann and Reichstein, 2008), but the most uncertain component of the terrestrial C cycle is belowground (Pan et al., 2011). There is a great need to improve our understanding of soil C dynamics following deforestation and degradation especially in tropical forest regions. Most tropical forest deforestation studies concern conversion to pasture in the neotropics (e.g. Murty et al., 2002; Paul et al., 2008; Marin-Spiotta et al., 2009). Some recent studies have now reported on the Brazilian cerrado conversion to soy (Miranda et al., 2016); but few investigations have been done elsewhere (e.g. the Western Ghats, India – Debasish-Saha et al., 2014).

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Overall most studies on soil structure and soil C have been conducted on wetlands, peatlands, and permafrost soils at high latitudes (Post and Kwon, 2000; Davidson and Janssens, 2006). In these soils, decomposition proceeds slowly and organic matter accumulates. In contrast, turnover rates in the wet tropics are much faster with higher ecological productivity. The fast rates and complex interactions between the microbiota, soils and climate in tropical biomes increase the complexity of both understanding and estimating C budgets. Soils can act either as a source or as a sink for atmospheric carbon dioxide (CO_2) depending on land cover change and management (Guo and Gifford, 2002; Marin-Spiotta et al., 2009; Pan et al., 2011).

There has been increased global attention and literature review on the ability of tropical forests and soils to expedite nutrient cycling and C sequestration (Silver et al., 2000; Powers et al., 2011; Ryan et al., 2011; Sang et al., 2013). In Africa and South America, research networks and long term monitoring sites have been established, but in Asia reviews have revealed there is insufficient data even to make robust estimates (Pan et al., 2011). In South and Southeast Asia, forests are being converted to agricultural lands, and many of these lands are cultivated for only a short period of time and then abandoned due to rapid loss of productivity (Grainger, 1988; Brown et al., 1993; Miettinen et al., 2011). Many of these abandoned agricultural lands have been reforested; the global area of tree plantations established by 2005 was 109 million ha with Asia accounting for 41% of the total, mostly in China (Sang et al., 2013).

Land conversion causes changes in the quality, quantity, timing, and spatial distribution of soil C input, but these effects are poorly characterized in the tropics (Don et al., 2011; Sang et al., 2013). Little is known about how soil C and nitrogen (N) pools change with deforestation and conversion of forest land to commercial agricultural crops such as tea, rubber, and oil palm (Guillaume et al., 2015). Still fewer studies have measured effects of abandonment and subsequent development of second growth or planned reforestation with tree plantations on soil C and N (Silver et al., 2000; Marin-Spiotta et al., 2009). The efforts of assessing terrestrial C stocks rely largely on literature reviews or coarser assessments by remote sensing techniques due to the difficulties and absence of long-term field measurements. For instance, plantations composed of Caribbean pine (*Pinus caribaea*) are considered useful for reforestation, but this does not necessarily mean these plantations are restoring soil fertility or structure. This species is used for its timber, pulp, and resin, it is resilient to fire, and is effective at soil stabilization (Critchfield and Little, 1966). In addition, several studies on Caribbean pine plantations suggest it can improve soil water holding capacity and fertility of degraded soils formerly used for agriculture (Ashton et al., 2014b).

Although Caribbean pine has shown potential for reforestation of open lands that were formerly tropical forests throughout Asia and Latin America (Brown et al., 1983; Berlyn et al., 1991), effects on soil properties in comparison with former land uses have not been quantified. There have been no studies on the effect of Caribbean pine plantations on highly weathered and erodible Ultisols (USDA, 1975); a soil order that is prevalent across tropical wet regions of South and Southeast Asia (Ashton et al., 2011; Don et al., 2011; Yulnafatmawita and Anggriani, 2013). The major composition of a highly weathered ultisol is low activity clay that has a cation exchange capacity <4 $cmol_c$/kg soil (Powers et al., 2011); a substrate texture that provides less mineral surface for cation exchange capacity and hence chemical attributes of soil fertility (Lal, 1987; Brady and Weil, 1996; Don et al., 2011). Understanding the capacities of clay-based ultisols to trap and bind soil C is a key factor that determines physical soil structure, stability, water holding capacity, and aeration. Also, soil organic matter (SOM) is considered the best soil binding agent for stabilizing soil aggregates and increasing soil water capacity, which affects the C and N content of microbial biomass and in turn can sequester more C and N (Jandl et al., 2007; Yulnafatmawita and Anggriani, 2013). The vegetation type covering the land surface is a major source of C and organic matter to the mineral soil; forest clearance and agricultural land use change in tropical regions potentially has a negative impact on soil structure (bulk density, soil texture) and chemistry (cation exchange capacity, P, Mg, K) and on the balance of soil C and N, which are important determinants for soil fertility and productivity (Murty et al., 2002; Marin-Spiotta et al., 2009; Miranda et al., 2016).

In this study, we investigated soil structure and chemistry with special focus on C and N in relation to conversion of rain forest to a major agricultural land use and subsequent vegetation changes after agricultural abandonment. We did this because the soils of the study site, ultisols, and the Asian mixed-dipterocarp rainforest region broadly, have a strong argillic B-horizon, and surface horizons that are sandy in texture with poor cohesive structure making them very sensitive to land use impacts (Yulnafatmawita and Anggriani, 2013). In our study these soils are on slopes and hilly terrain making their close to surface horizons very susceptible to nutrient depletion and erosion from cultivation.

We studied the original mixed-dipterocarp rain forest (1); its conversion to tea plantations (2); tea lands that had been abandoned and reverted to Kekilla fernlands (*Dicranopteris linearis*) (3); and Kekilla fernlands that had been planted with Caribbean pine (4). By comparing the physical and chemical soil properties of these land types with undisturbed rain forest, we established baseline data to determine influence of agriculture, abandonment, and reforestation on soil properties. Soil organic carbon (SOC) was identified by verifying variables (i.e. SOC concentration and its relation to N, soil bulk density, and sampling soil depth) and demonstrating the interactions between the variables. Natural abundance of C and N isotopes and their ratio ($\delta^{13}C$ and $\delta^{15}N$) was measured to distinguish the influence of aboveground land cover on origins of soil C (Diochon and Kellman, 2008). Relative abundance ratios of ^{12}C and ^{13}C or ^{14}N and ^{15}N have been used to infer changes in such soil attributes as soil texture, plant species, SOM quantity and quality with phase of land use (Brunn et al., 2014). Measures of soil pH, cation exchange capacity, phosphorus, potassium and magnesium were done to assess changes in soil chemistry with land use.

2. Materials and methods

2.1. Site description

This study was conducted in 2014 within and around the Sinharaja World Heritage Site, located in the lowland wet zone of Southwest Sri Lanka (6°21′–6°27′N; 80°21′–80°38′E) (Fig. 1). The topography of this region consists of a series of parallel ridges and valleys aligned east-west (Gunatilleke et al., 2006). The average elevation is about 350 m, but our study site varies in elevation between 300 and 600 m (asl) (Ashton et al., 2001; Table 1). Mean annual temperature is 25–27 °C with little annual variation (±4 °C) (Ashton et al., 1997, 2011; Shibayama et al., 2006). Mean annual precipitation (MAP) varies between 4000 and 6000 mm and is distributed relatively evenly throughout the year with a minimum of 198 mm in February and a maximum occurring during the southwest (May–July) and northeast (October–January) monsoonal periods (Ashton et al., 1997). The high rainfall accelerates bedrock and soil weathering processes; the bedrock consists of khondolites and garnetiferous charnokites with more recent gravels, sands, and clay (Wijepala, 1958). Soils are classified as ferruginous ultisols with a strong argillic B horizon and A/E horizons that is sandy and poorly structured and very erodible on steep slopes

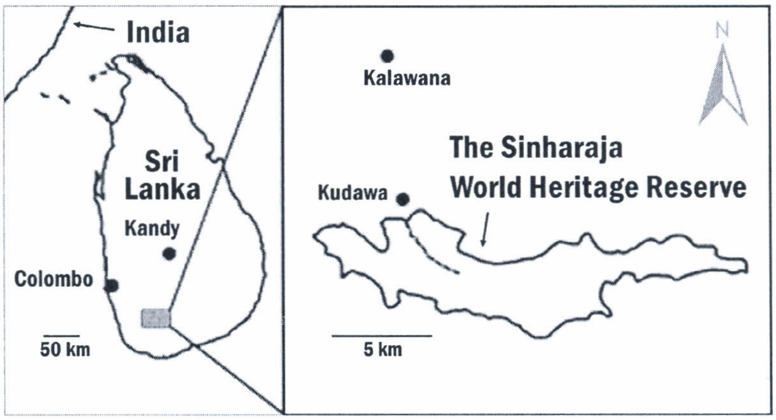

Fig. 1. (a) The location of the Sinharaja World Heritage Forest in southwest Sri Lanka; (b) the four village study sites are all located in and around the western boundary of the Sinharaja World Heritage Forest near Kudawa village.

Table 1
Site conditions and top soil attributes of tea plantations, kekila fernlands, Caribbean pine plantations, and mature forests. Different letters within columns denote significantly different means between land uses based on one-way ANOVA and Tukey's post hoc test with $P < 0.05$. n indicates the number of replicates. OM is organic matter. BD is soil bulk density. RM is the mass proportion of rock fragment content (NA = not available, NS = not significant).

Land uses	Elevation range (m)	Slope range (°)	Year of establishment	Mass of OM*** (kg m^{-2})	BD*** (g cm^{-3})	RM (%)	
n	16	16		48	48	16	
						Soil depth 0–10 (cm)	*10–20*
Tea plantations	326–392	16–34	1950s	NA	1.12 (0.10) a	17.0 (10.04) NS	18.2 (9.40) NS
Kekilla fern lands	377–409	10–20	1970s	NA	0.71 (0.13) b	15.7 (6.80) NS	20.1 (8.75) NS
Caribbean pine plantations	346–427	18–34	1978–1982	2.1 (0.43) a	0.79 (0.13) b	12.5 (7.32) NS	21.8 (10.40) NS
Mature forests	379–673	10–33	Mature – old growth	1.4 (0.31) b	0.78 (0.17) b	17.2 (4.68) NS	19.3 (7.69) NS

*** p-value < 0.0001.

(Panabokke, 1996; USDA, 1975; Ashton et al., 2001). Ultisols are the widespread and most common kind of soil that characterizes mixed dipterocarp rainforest throughout their distribution in Southeast Asia (Ashton et al., 2011).

Southwest Sri Lanka has a well-documented land use history, with a broad spectrum of land use. The Sinharaja Forest remains as one of the few undisturbed rainforests within the region comprising 20,000 ha. It was designated as a UNESCO World Heritage site in 1988 (Gunatilleke et al., 2006). Local communities around the Sinharaja forest live by mostly cultivating tea, harvesting non-timber forest products, and generating a small amount of income from tourism. Tea plantations were created from cleared forest lands since the 1950s but because of soil erosion many plantations were abandoned and reverted to Kekilla fern (*Dicranopteris linearis*). Kekilla fern is a widely distributed fern species throughout Asia. This rhizomatous fern mostly reproduces via vegetative cloning through is roots. Kekilla fernlands are fire dependent and often burned by people repetitively (Ashton et al., 2014a, 2014b). Fire kills most of the fire sensitive rain forest regeneration that might establish; but post-fire, Kekilla fern re-sprouts and grows prolifically shading out any regeneration that might establish. This is therefore a continuous cycle of fire and fern-regrowth (Cohen et al., 1995). Consequently, land managers characterize Kekilla fernland as degraded and from 1978 to 85 embarked on an ambitious program of fernland reforestation using fire adapted Caribbean pine (Fig. 2) (Ashton et al., 1997; Shibayama et al., 2006). Almost all the pine around the Sinharaja was planted between 1978 and 1982 at 2 m × 2 m spacing on fernlands that had established after tea land was abandoned (Ashton et al., 1997, 2001).

In our study we examined three land uses that are all chronologically linked to forest clearance for tea plantations that occurred in the 1950s. These comprise tea plantations that have been in use for over 50 years; tea lands that have been "abandoned" and reverted to Kekilla fernlands in the early 1970s; and tea lands that reverted to Kekilla fernlands in the early 1970s and that were subsequently planted to Caribbean pine between 1978 and 1982. These three land uses were compared to nearby undisturbed rain forest within the Sinharaja forest (Fig. 2).

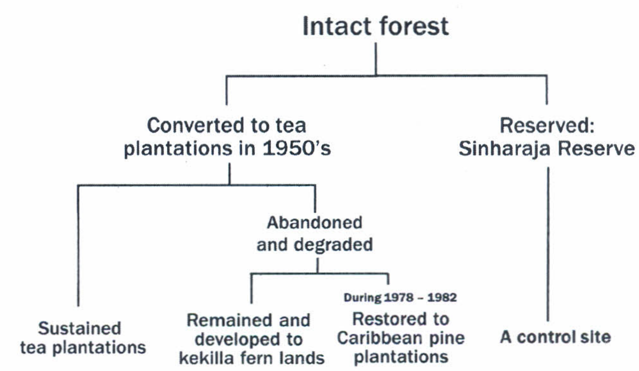

Fig. 2. A diagram of the four different land uses in southwest Sri Lanka adjacent to the Sinharaja World Heritage Site. Tea plantations were formed in 1950s from cut, burned and cleared rainforest by small-holders. In the early 1970s some of these tea plantations were abandoned because they were illegally created on State lands. These lands reverted to fern lands and then a subset was reforested with Caribbean pine plantations established between 1978 and 1982 to demarcate the buffer zone and boundary of the Sinharaja Forest.

2.2. Sampling scheme

Four replicated sites of tea plantations, Kekilla fernlands, and Caribbean pine plantations were selected from four villages

(Pitakele, Kudawa, Petiya Kanda, and Ketala Paththala), all surrounding the northwest boundary of the Sinharaja forest (Fig. 1). For comparison we randomly selected four sites in the Sinharaja forest adjacent to the four villages and that were representative of the topographic positions, aspects, slope and soils of the land use sites sampled. Elevation ranged from 300 m to 600 m (asl), all sites were ultisols on mid-slope topography.

We estimated that between 10 and 20 replicate samples would be sufficient to detect differences in SOC and chemical properties for each soil depth of 0–10 cm and 10–20 cm (Zar, 1984; Waldchen et al., 2013). At each of the four replicate sites for a land use type, four 10 m × 10 m sub plots were randomly established for soil measurements (4 site replicates × 4 subplots, n = 16). A composite soil sample (from five randomly collected subsamples) was taken within each 10 m × 10 m plot (Goidts et al., 2009). Sampling was done with au auger at two soil depths (0–10 cm and 10–20 cm). For each depth composite samples were further used to analyze rock fragment content (RM). We intentionally sampled close-to-surface soil horizons as they have been proven to be the most sensitive to impacts of land use change (Ellert et al., 2001; Gifford and Roderick, 2003).

Three intact cores (core diameter = 7.2 cm) were additionally taken within a plot to measure the corresponding soil bulk density (BD). In order to minimize an underestimation of the effective rock fragment content, we selected the BD sampling points randomly with a core of relatively large diameter (4 sites × 4 plots × 3 subsamples = 48 BD soil samples per land use). Three sampling points were selected to collect all the surface organic matter immediately above the mineral soil using a 20 cm × 20 cm frame (4 sites × 4 plots × 3 subsamples = 48 organic layer samples per land use). The organic matter comprised fallen leaf litter (incorporated and unincorporated) above the mineral soil surface. Samples of the surface organic matter were only collected from pine plantations and the rain forest. Tea plantations comprise no accumulated litter layer, and the soil surface of Kekilla fernlands is densely covered by a meter-high interwoven fern biomass. Organic matter was oven dried at 70 °C for three days and weighed to measure average dry mass on 1 m^{-2} of soil surface for pine plantations and rain forest (Table 1).

2.3. Sample preparation and analyses

Mineral soil samples were air dried and sieved <2 mm to remove stones. Stone mass was measured to acquire rock fragment content (RM). Soil pH was measured with H_2O extraction. cation exchange capacity (CEC), phosphorus (P), magnesium (Mg), potassium (K), nitrogen (N), and carbon (C) were determined at the soils laboratory of the Rubber Research Institute of Sri Lanka (Carter, 1993; Pansu and Gautheyrou, 2007). Available nutrients and organic carbon were extracted to 1 M (mol/L) ammonium acetate buffered to pH 7 by using Kjeldahl digest according to Walkley and Black (1934) in the same manner as Tomimura et al. (2012). In order to measure the natural abundance of C and N isotopes, the <2 mm fraction of the soil was homogenized by grinding the sample on a cryogenic grinder chilled by liquid N. The ground soils were acidified with 0.5 M HCI to remove inorganic C, which is mainly in a carbonate form. Isotopes of $\delta^{13}C$ (‰), and $\delta^{15}N$ (‰) in processed soil samples were analyzed using a Costech ESC 4010 Elemental Combustion System (Costech Analytical Technologies, Valencia, CA, USA) interfaced with a Thermo Finnigan Delta Plus Advantage isotope ratio mass spectrometer (Thermo Finnigan-MAT, Bremen Germany).

2.4. Calculations and statistical analyses

Organic carbon stocks and nitrogen stocks (Eqs. (1) and (2)) for fixed soil volumes for the two soil depths (i) were calculated based on bulk density (BD, Eq. (3)), the relative contribution of rock fragment content (RM, Table 1), layer thickness, and element concentration. They can be characterized as:

$$C\ stock\ (\mathrm{kg\ m^{-2}}) = \frac{d \times C \times BD \times [1 - RM]}{100} \tag{1}$$

$$N\ stock\ (\mathrm{kg\ m^{-2}}) = \frac{d \times N \times BD \times [1 - RM]}{100} \tag{2}$$

where d is the sampling depth considered (cm), C and N is the soil organic C and nitrogen concentration (g kg^{-1}), BD is the bulk density (g cm^{-3}), and RM is the mass proportion (%) of rock fragment content (Goidts et al., 2009). Dry mass concentrations (w/%) were converted into dry volume concentration (g m^{-2}) using dry bulk density measurements (t m^{-3}).

$$BD\ (\mathrm{g\ cm^{-3}}) = \frac{total\ dry\ mass\ of\ sample\ (\mathrm{g})}{volume\ of\ soil\ core\ (\mathrm{cm^3})} \tag{3}$$

The average dry mass of collected organic layer was calculated using the equation below (Eq. (3)):

$$Organic\ layer\ (\mathrm{kg\ m^{-2}}) = \frac{oven\ dry\ weight\ of\ litter\ (\mathrm{kg})}{sampled\ area\ (\mathrm{m^2})} \tag{4}$$

Natural abundance of isotopes are expressed as the relative difference between the sample and the standard (Pee Dee Belemnite (PDB) for C), according to:

$$\delta^{heavy\ isotope}\ \mathrm{element}\ (‰) = \left[\frac{R_{sample}}{R_{standard}} - 1\right] \times 1000 \tag{5}$$

where R_{sample} and $R_{standard}$ are the ^{13}C:^{12}C abundance ratios of the sample and reference standard Vienna-PeeDee belemnite (V-PDB), respectively. Negative values mean that ^{13}C is less abundant than in the reference standard. δ is the ratio of the heavy/light isotope content of the element ($\delta^{13}C$ of $^{13}C/^{12}C$ and $\delta^{15}N$ of $^{15}N/^{14}N$). In order to understand the relationship of soil $\delta^{13}C$ and $\delta^{15}N$, we used simple correlation analyses (Peri et al., 2012).

All measured variables were first characterized by classical descriptive statistics (mean and standard errors). One-way ANOVA was used to evaluate the differences in each variable by soil depth and land uses with Tukey's Least Significant Difference (LSD) for pair-wise comparison. Statistical analyses were performed in SPSS Version 22 (SPSS Software 2013, IBM SPSS Inc., Chicago, IL, USA). Finally, Model II linear regression analyses were done to compare relationships between $\delta^{15}N$ and $\delta^{13}C$ for the different land uses (Ludbrook, 2012).

3. Results

3.1. Soil characteristics

The topographic differences among land uses were very similar in almost all circumstances with little difference among sites in regards to slope or elevation. One noticeable exception was that the elevation range of sites sampled across the mature forest was higher than the elevation ranges of the other land uses. This can primarily be attributed to the fact that the forest is surrounding the villages that are all positioned along the river valleys where the land is cultivated for rice.

The organic matter above the mineral soil is higher in Caribbean pine plantations compared to the organic matter of mature forest (2.1 ± 0.43 kg m^{-2} and 1.4 ± 0.31 kg m^{-2}, respectively). Measurements were not made in the tea plantations where no surface organic matter was present; or in the fernlands where the fronds were densely intertwined and about one meter in depth. Tea plantations show higher bulk density (BD) as compared to the other

Table 2
Means and standard deviations of soil properties for land uses at soil depth 0–10 and 10–20 cm: tea plantations (tea), kekila fern lands (fern), Caribbean pine plantations (pine), and mature forests (forests). Different letters within columns denote significantly different means (a > b > c) between land uses based on one-way ANOVA and Tukey's post hoc test with $P < 0.05$ (n = 16, NS = not significant).

Soil depth	Land uses	pH	CEC ($cmol_c$/kg)	P (mg kg^{-1})	K (mg kg^{-1})	Mg (mg kg^{-1})
0–10 (cm)	Tea	4.39 (0.34) a	3.73 (0.06) a	24.34 (24.95) a	116.41 (57.44) a	45.81 (28.87) ab
	Fern	4.46 (0.16) a	2.86 (0.30) b	4.97 (4.15) b	42.47 (12.99) b	55.01 (11.33) a
	Pine	4.59 (0.27) a	3.16 (0.27) ab	4.59 (3.93) b	24.49 (16.12) b	31.31 (10.76) b
	Forests	4.12 (0.18) b	3.44 (0.21) ab	5.98 (4.44) b	34.67 (18.28) b	42.54 (13.76) ab
10–20 (cm)	Tea	4.29 (0.44) bc	3.37 (0.10) NS	18.08 (24.11) a	60.96 (22.39) a	29.09 (16.64) ab
	Fern	4.50 (0.12) ab	3.06 (0.22) NS	5.51 (7.26) b	20.32 (10.01) b	30.90 (7.21) a
	Pine	4.63 (0.24) a	3.08 (0.16) NS	2.82 (2.08) b	14.58 (13.99) b	20.80 (4.59) b
	Forests	4.17 (0.17) c	3.60 (0.10) NS	5.33 (4.22) b	21.42 (9.34) b	28.31 (8.13) ab

land uses (Table 1). This should not be surprising given tea is the only land use with significant current and ongoing impacts of soil cultivation and compaction from human foot traffic. Rock fragment content (RM%) shows no difference among land uses.

The average soil pH values of mature forests are 4.12 ± 0.18 at 0–10 cm soil depth and 4.17 ± 0.17 at 10–20 cm soil depth. Interestingly, these values are much lower than the other lands that were cleared (Table 2). The soil pH for Caribbean pine show highest values with 4.59 ± 0.27 at 0–10 cm soil depth and 4.63 ± 0.24 at 10–20 cm.

A variety of soil fertility measures (e.g. CEC ($cmol_c$ kg^{-1}) P, K and Mg), are much higher in tea plantations as compared to the other land uses, although the standard deviations demonstrate significant variation within and across the sites (Table 2). Except for CEC this pattern is consistent at both soil depths. Caribbean pine, though not significantly different from the other non-tea land uses, is consistently the lowest in both nutrient concentrations and CEC. Kekilla fernlands show the highest Mg values with 55.01 ± 11.33 (mg kg^{-1}) at 0–10 cm soil depth and 30.90 ± 7.21 (mg kg^{-1}) at 10–20 cm compared to the other land uses (Table 2).

3.2. Soil carbon and nitrogen

Soil organic C concentrations in tea plantations (2.03 ± 0.34) are lower than other land uses at 0–10 cm. At the lower soil depth, C concentrations decrease in all land uses, but fernlands show the highest C concentration (Table 3). On the other hand, when C concentration values are used to calculate soil organic carbon stocks (SOC) using bulk density (BD) as a component (see Eq. (1)), SOC values for tea plantations are higher than the other land uses at both depths. The impacts can only be attributable to soil compaction in tea plantations (Table 3).

The N (%) values are significantly higher in Kekilla fernlands and mature forest at both soil depths. Calculations of soil organic N stocks (SON) from N concentration and measures of BD (Eq. (2)), reflect the same patterns as for SOC with highest SON in tea plantations at both depths compared to other land uses. (Table 3). Caribbean pine plantations show the lowest SON stocks at both soil depths.

While there is no differences in CN ratios among land uses at 0–10 cm depth, at 10–20 cm Caribbean pine plantations and Kekilla fernlands show significantly higher values than other land uses.

3.3. Soil $\delta^{13}C$ and $\delta^{15}N$

In general, soil $\delta^{13}C$ values are significantly different among land uses ($p < 0.05$), and between the two soil depths. The mean $\delta^{13}C$ values of all land uses increase with depth (see Fig. 3). Kekilla fernlands show the highest $\delta^{13}C$ values at both depths (−26.69 ± 0.43‰ at 0–10 cm and −26.17 ± 0.50‰ at 10–20 cm) while mature forest exhibits the lowest (−28.07 ± 0.37‰ at 0–10 cm and −27.41 ± 0.38‰ at 10–20 cm). Caribbean pine plantations show the greatest increase in $\delta^{13}C$ value as to other land uses on progressing from surface to the deeper soil depth (e.g. −27.82 ± 0.38‰ at 0–10 cm to −26.50 ± 0.37‰ at 10–20 cm).

Similarly, $\delta^{15}N$ values of all land uses increase with increasing soil depth (Fig. 4). Mature forests show the lowest $\delta^{15}N$ values at both 0–10 cm and 10–20 cm with 2.96 ± 0.64‰ and 4.31 ± 0.51‰ respectively. Tea plantations have highest $\delta^{15}N$ at 0–10 cm depth but at the deeper depth (10–20 cm) $\delta^{15}N$ values of tea, Kekilla fernlands and Caribbean pine plantations show no difference.

We used linear regressions to define the relationship between soil $\delta^{13}C$ and $\delta^{15}N$ for combined soil depths and for each of the different land uses. Interestingly, compared to the other land uses, tea plantations showed much higher $\delta^{15}N$ values relative to their corresponding $\delta^{13}C$ and mature forests were much lower (see Fig. 5). For both Kekilla fernlands and Caribbean pine plantations the relationship between $\delta^{13}C$ and $\delta^{15}N$ was strongly linear with the heavier the isotope natural abundance of C in soils, the more enriched the sample in the ^{15}N isotope; Kekilla fernlands ($R^2 = 0.6533$) and Caribbean pine ($R^2 = 0.9235$). These relationships were much weaker for tea and forest. The results showed that the heavier the isotope natural abundance of C in soils, the more enriched

Table 3
Means and standard deviations of soil organic C (%), N (%), C:N ratio, soil organic carbon stocks (SOC kg m^{-2}) and soil nitrogen stocks (kg m^{-2}) at different soil depths 0–10 cm and 10–20 cm under the different land uses: tea plantations (tea), kekila fern lands (fern), Caribbean pine plantations (pine), and mature forests (forests). Different letters within columns denote significantly different means (a > b > c) among land uses based on one-way ANOVA and Tukey's post hoc test with $P < 0.05$ (n = 16, NS = not significant).

Soil depth	Land uses	C (%)	N (%)	C:N ratio	SOC (kg m^{-2})	Soil N stock (kg m^{-2})
0–10 (cm)	Tea	2.03 (0.34) b	0.22 (0.06) b	10.86 (7.02) NS	1.89 (0.43) a	0.20 (0.06) a
	Fern	2.67 (0.16) a	0.25 (0.05) ab	11.27 (2.43) NS	1.60 (0.17) b	0.15 (0.03) bc
	Pine	2.44 (0.32) a	0.20 (0.06) b	13.29 (4.84) NS	1.71 (0.30) ab	0.13 (0.06) c
	Forests	2.49 (0.33) a	0.28 (0.07) a	9.18 (1.58) NS	1.61 (0.23) b	0.18 (0.04) ab
10–20 (cm)	Tea	1.76 (0.35) b	0.17 (0.05) ab	9.95 (3.20) b	1.51 (0.59) a	0.16 (0.06) a
	Fern	2.26 (0.34) a	0.21 (0.05) a	11.25 (2.42) ab	1.28 (0.23) ab	0.12 (0.03) bc
	Pine	1.83 (0.40) b	0.15 (0.07) b	14.24 (6.49) a	1.14 (0.31) b	0.09 (0.05) c
	Forests	1.86 (0.47) b	0.22 (0.05) a	9.01 (2.69) b	1.15 (0.23) b	0.14 (0.04) ab

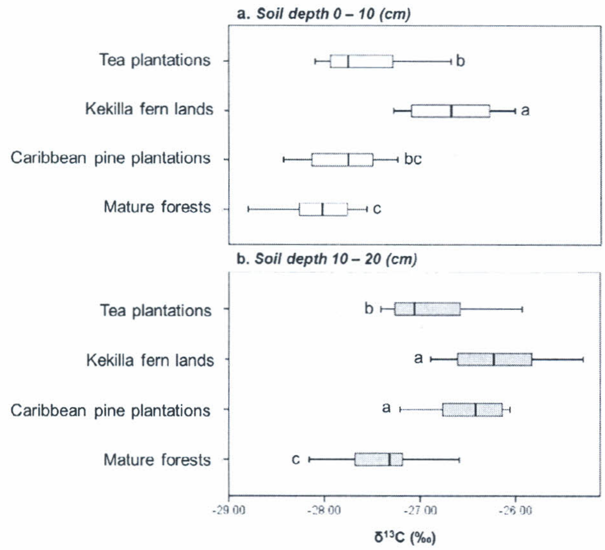

Fig. 3. Box plots depicting means and their variation for soil $\delta^{13}C$ (‰) at soil depth 0–10 cm and 10–20 cm under different land uses (n = 16, Tukey LSD used for ANOVA ($p < 0.05$)).

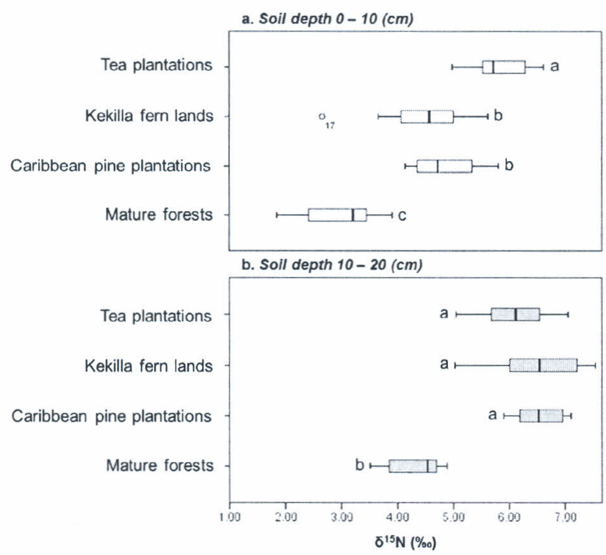

Fig. 4. Box plots depicting mean and variation for soil $\delta^{15}N$ (‰) at soil depth 0–10 cm and 10–20 cm under different land uses (n = 16, Tukey LSD used for ANOVA ($p < 0.05$)).

was the sample in the ^{15}N isotope; Kekilla fernlands ($R^2 = 0.6533$) and Caribbean pine ($R^2 = 0.9235$).

4. Discussion

4.1. Differences in measures of soil structure and fertility between land uses

By having Sinharaja Rain Forest Reserve as a baseline site, we are able to compare physical and chemical properties of soils across a chronosequence of land use change from existing tea plantations that are currently intensively managed and have been managed almost in the same manner for the last fifty to sixty years; to lands that underwent the same transformation to tea at the same time but were subsequently abandoned and reverted to Kekilla fernland in the late 1960s and early 1970s, a subset of which were reforested to Caribbean pine between 1978 and 1982. This provides a rare and unique opportunity to examine change in soil structure with land conversion and subsequent abandonment. Though this process occurs worldwide few studies have examined such impacts and soil forming processes because of a combination of an absence of knowledge on land use history and the rarity of a circumstance where such a diversity of land use trajectories is available and comparable to the original forest.

Past studies on land use change have shown that input of organic matter (OM) can play a key role influencing dynamics of C and N in soils (Guo and Gifford, 2002; Don et al., 2011; Sang et al., 2013; Weissert et al., 2016). In our study unincorporated surface OM in tea plantations was negligible while in Kekilla fernlands it was so large it was not measurable (Cohen et al., 1995). The amount of OM in tea plantations is limited and varies depending on the frequency of tea harvesting, management and maintenance activities, and rates of decomposition (Wijeratne, 1996). The surface OM layer in Kekilla fernlands is an interwoven layer of dead stems and fern fronds that is difficult to separate and can amount to one meter in thickness. However, Caribbean pine plantations and mature rain forest have a well-defined OM layer of fallen leaves and pine needles that show varying levels of incorporation (Table 1). It is not surprising that unincorporated amounts of litter are highest for pine and Kekilla fernlands given their known slow decomposition rates (litter decomposition rate, $k = 0.164$) and low nutritional value to soil microbes (Maheswaran and Gunatilleke, 1988). Presumably what litter does fall on the soil beneath tea is quickly incorporated into the mineral soil (Wijeratne, 1996).

In addition to critical soil properties, such as soil pH, cation exchange capacity (CEC), soil carbon (C), and nitrogen (N), we measured representative elements for soil fertilization (phosphorous (P), potassium (K), and magnesium (Mg)). We did this in order to measure the legacy of fertilization in tea plantations and its after effects with land abandonment and its potential interaction with fire on abandoned lands. Although these elements are the ones mostly rapidly removed from the soil by plants and microorganisms, the quantitative difference between land uses allow us to infer the impacts that both fertilization and fire may have when they revert to Kekilla fernlands and in cases to reforestation with Caribbean pine. In particular, P and K in tea plantations is dramatically higher than all other land uses for both soil depths. This can only be attributed to the fertilization effect – no difference can be detected between the rain forest and the remaining non-tea land uses suggesting that there is not much of any legacy effect (Table 2). However, there appears to be a legacy effect of fertilization and/or fire on pH. All converted lands have higher pH than the original forest and that at lower soil depths this becomes more amplified with Kekilla fern and pine exhibiting the highest pH perhaps because of their exposure to multiple past surface fires (Certini, 2005; Shibayama et al., 2006).

Although combustion of the surface soil horizon can increase the immediate availability of some nutrients, it also can raise soil alkalinity and cause OM loss and in turn, decrease cation exchange capacity (CEC), organic chelation, aggregate stability, macro pore space, infiltration, and soil microorganisms (Certini, 2005; Shibayama et al., 2006). While our mature forest soils were lowest in pH, Kekilla fernlands and pine plantations showed the lowest CEC values at the shallower soil depth again suggesting a legacy affect from past land use. In general CEC values among land uses were relatively low, ranging from 2.86 ($cmol_c\ kg^{-1}$) to 3.73 ($cmol_c\ kg^{-1}$) as compared to temperate climate zones; for example, sandy soils low in organic matter in North America can have CEC less than 3 ($cmol_c\ kg^{-1}$) (Bergstrom et al., 1987). In our study, like others, land use did not alter proportions of clay content and by

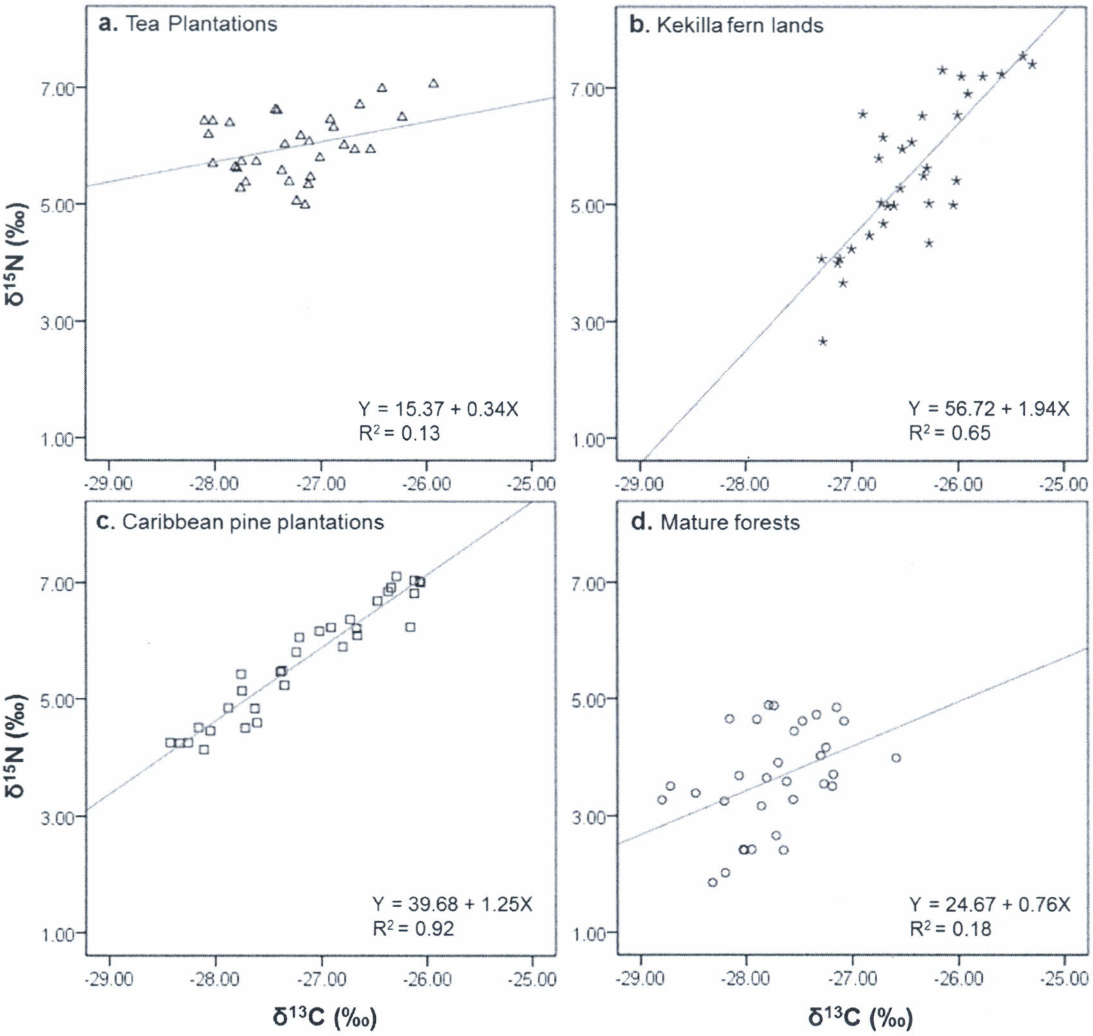

Fig. 5. Linear regression relationships between the $\delta^{15}N$ (‰) and $\delta^{13}C$ (‰) values in soils of each land use ($n = 32$, $p < 0.05$).

implication CEC (Panabokke, 1996; Ma and Eggleton, 1999). In a meta-analysis on tropical soil C stock changes in relation to land use change Powers et al. (2011) categorized soils with CEC under 4 ($cmol_c\ kg^{-1}$) as lower activity soil, indicating more susceptible soil C to land use change in particular. According to this categorization system, the soils in our site belong to lower activity soil.

4.2. SOC stock and N stocks

The measurement of soil organic carbon (SOC) and nitrogen (N) stocks can vary depending on soil depth (Guo and Gifford, 2002; Marin-Spiotta et al., 2009). The internationally recommended practice in C accounting (IPCC, 1997) recommends using the mass of organic C per unit ground area to a depth of 30 cm as soil C stocks. Many studies have focused on the surface mineral soil or topsoil as the most influenced by land use and land cover changes in tropical biomes (Lugo et al., 1990; Sa et al., 2001; Wilcke and Lilienfein, 2002; Gifford and Roderick, 2003; Baillie et al., 2006; Powers et al., 2011; Peri et al., 2012; Sang et al., 2013). However, studies have shown influences of land use at much deeper depths related to physical and chemical soil properties: Veldkamp et al., 2003 (total organic C, N, $\delta^{13}C$ at 2.5 m soil depth), Don et al., 2011 (SOC, bulk density, at 0.2–1 m soil depth), and Guillaume et al., 2015 (total C and N, $\delta^{13}C$ at 1 m soil depth). In our study, we focused on SOC and N stocks in the surface horizons at two separate depths from 0 to 10 cm and from 10 to 20 cm primarily because ultisols have surface horizons that are sandy in texture making them very sensitive to land use impacts (Yulnafatmawita and Anggriani, 2013).

Some of the soil properties of mature forests in the Sinharaja, as baseline data, are comparable to ultisols at depth 0–10 cm of tropical rain forests at the La Selva Biological Station in Costa Rica (Perez et al., 2000). For example, bulk density (BD) was similar (La Selva – 0.69 $g\ cm^{-3}$ versus Sinharaja – 0.78 $g\ cm^{-3}$), but C and N values in La Selva were twice as much as that of the Sinharaja (total C was 5.71%, total N was 0.46%, and C:N ratio was 12.32 at La Selva). Ultisols of the old metamorphic rocks in the Sinharaja are therefore relatively infertile compared to the younger volcanic rocks and sediments of Central America but more fertile as compared to the old nutrient poor sedimentary rocks of Borneo; sandstone sites showed organic C of 1.91% and total N of 0.14% as well as shale clay sites had organic C 1.21% and total N 1.21% at 0–10 cm topsoil (Baillie et al., 2006).

In our study the C concentration (%) of mature Sinhajara forest was not significantly different from other land uses at both soil depths, except for tea which was predictably lower; and Kekilla fern which was higher at lower depth. However, N (%) was higher for the forest and Kekilla fernlands as compared to the other two land uses at both depths. This pattern continued with N stocks ($kg\ m^{-2}$) of mature forests being higher than Kekilla fernlands and Caribbean pine plantations; but not for tea land which was fertilized. Wilcke and Lilienfein (2002) examined Caribbean pine plantation soils at depth 0–30 cm in Brazil. Values of C (1.9%) and N (0.12%) were similar to our study. Though the C:N ratio showed no difference at 0–10 cm depth the ratios were predictably the highest for pine and Kekilla fernlands, presumably because the fronds, $k = 0.164$ (Maheswaran and Gunatilleke, 1988), and Caribbean pine needles, $k = 1.5$ (Cuevas et al., 1991), are slower to decompose and the nitrogen is more tightly bound to the organic matter (Table 3).

In many SOC studies, the bulk density (BD) has been regarded as one of the key determinants for more precise SOC and N stock measurements (Gifford and Roderick, 2003; Goidts et al., 2009; Don et al., 2011; Weissert et al., 2016). Measuring the BD, however, can be cumbersome due to practical difficulties in sampling intact soils and their susceptibility to falling apart. It has therefore often been omitted from sampling and instead calculated indirectly from other measurements, usually resulting in biased estimates of soil carbon stocks (Gifford and Roderick, 2003; Don et al., 2011; Powers et al., 2011). In addition, site disturbance such as surface soil compaction, if not recorded, could be another source of error in measuring soil C and N stocks. Given that we measured BD and recorded the nature of potential land use impacts, our study both clarifies and demonstrates some of these effects. In our study, BD is clearly affected by compaction in tea plantations (Table 1). This suggests that tea plantation soils store more C that other land uses, despite lower C concentrations (Lee et al., 2009). Weissert et al. (2016) discussed this issue with compacted soils of different urbanized lands in New Zealand. Although soil compaction was evident in grasslands, they concluded that grass dominated soils have higher SOC stocks irrespective of compaction compared to urban forest soils at 0–10 cm depth, emphasizing an important role of grassland storing more C than urban soils. However, without considering SOC and N stocks of tea plantations, Caribbean pine plantations had relatively higher SOC with a 0.1 kg m^{-2} difference compared to other land uses at 0–10 cm.

Carbon to nitrogen ratio (C:N) is an important measure of determining the availability of C and N to plants and microorganisms (Marin-Spiotta et al., 2009). More specifically, an increase in C:N ratio could be due to a larger increase in C relative to N, or a larger decrease in N relative to C. This ratio is a critical variable to predict decomposition processes with a higher C:N ratio indicating slower decomposition processes because of higher N immobilization. In our study, C:N was not significantly different among land uses at soil depths of 0–10 cm. However, at deeper horizons (10–20 cm), Caribbean pine plantations have higher C:N values followed by Kekilla fernlands. In contrast, tea plantations and mature forests were lower in C:N ratios suggesting that those sites have higher rates of decomposition presumably because organic inputs were more palatable and digestible to microorganisms (Eiland et al., 2001).

Studies by Wilcke and Lilienfein (2002) demonstrated that Caribbean pine needles have a higher C:N ratio along with a higher fiber proportion and recalcitrant chemicals, than broadleaves; and both these characteristics make pine needles have a slower decomposition rate (Cuevas et al., 1991). In this context, the significantly higher mass of the OM layer in Caribbean pine plantations and the high C:N ratio are connected because of the slower decomposition and recalcitrant C quality (condensed tannins, lignin) (Wilcke and Lilienfein, 2002; Hopkins et al., 2009; Hattenschwiler and Jorgensen, 2010).

4.3. Soil $\delta^{13}C$ and $\delta^{15}N$

Carbon and nitrogen isotopes and their species are associated with different biogeochemical turnover processes of C and N in soil; $\delta^{13}C$ and $\delta^{15}N$ have been used as integrative measurements in determining certain ecosystem processes (Ehleringer et al., 2000; Wynn et al., 2006). Higher $\delta^{13}C$ value (less negative) indicates that soil is enriched with the heavier isotope, ^{13}C, compared to lighter ^{12}C. There have been numerous studies demonstrating that ^{13}C enrichment increases proportionally with increasing soil depth (Garten et al., 2000; Wynn et al., 2006; Diochon and Kellman, 2008). This phenomenon is also applicable to $\delta^{15}N$. Mineral soil $\delta^{13}C$ and $\delta^{15}N$ are therefore depth dependent in naturally developing soils (Hogberg, 1997).

Fractionation factors involved with ^{15}N enrichment in soil are associated with various mechanisms that leads to loss of N (volatilization, nitrification, mineralization, leaching, and plant uptake), and these processes tend to leave the heavier N isotope behind (Hogberg, 1997; Peri et al., 2012). Billings and Richter (2006) monitored old-field pine forests over 40 years; ^{13}C and ^{15}N enrichment in deeper soils intensified with forest development. In our study, we observed this depth trend that $\delta^{13}C$ and $\delta^{15}N$ increased at deeper soil depth under all land uses (Figs. 3 and 4).

One explanation for a depleted $\delta^{13}C$ and $\delta^{15}N$ at shallow soil depths in forests has been attributed to the climate and tree composition. When the environment is moist with higher mean annual precipitation, as is the condition of tropical rain forest, plants tend to have lower water use efficiency (WUE) and a propensity to have high stomatal conductance (Peri et al., 2012). This subsequently allows plants to have higher intercellular CO_2 concentrations, and with this luxury, plants seemingly discriminate against heavier $^{13}CO_2$ in photosynthesis, resulting in lower $\delta^{13}C$ and therefore proportionately higher ^{12}C plant tissue values (Farquhar et al., 1989).

A second explanation for depleted $\delta^{13}C$ has been related to degree of C biosynthesis. Greater ^{13}C depletion occurs when assimilated C undergoes more steps of biosynthesis; for example, lignin and tannins are more ^{13}C depleted than cellulose (Garten et al., 2000; Preston et al., 2006). As an extreme example, Hopkins et al. (2009) examined ^{13}C and ^{15}N of soils in the Antarctic dry valley. They concluded that the high degrees of ^{13}C and ^{15}N depletion can be attributed to accumulation of lignified and recalcitrant organic matter relative to the litter of the original living vegetation. This suggests that the depth dependence trends of $\delta^{13}C$ in soils reported by many studies (e.g. Billings and Richter, 2006), is related to differential rates of OM decomposition and humification (Wynn et al., 2006). Furthermore, Werth and Kuzyakov (2010) also demonstrate that microbes can discriminate against heavier ^{13}C, resulting in enriched ^{13}C in soils after microbial mineralization processes in soils. Although there are numerous variables that are involved with heavier isotope fractionation within each process of SOM transformation, microbial decomposition processes in soil development can therefore also influence the relationship between the abundance of heavier C and N isotopes by preferred consumption and respiration of lighter isotopes (Staddon, 2004; Wynn et al., 2006; Peri et al., 2012).

In this study, the results of $\delta^{13}C$ and $\delta^{15}N$ of mature rainforest was distinctly depleted and different from the other three converted land types; the difference was shown at both soil depths (Figs. 3 and 4). Given the findings from other studies described above, it is most likely related to the quality and amount of litter input from the type and kind of vegetation associated with land use. Maheswaran and Gunatilleke (1988) studied the litter of the Sinharaja rain forest and demonstrated the turnover rate of C was relatively rapid in the range of half to one year as compared to Kekilla fern that was much greater than a year.

Among the four land uses in our study, Kekilla fernlands and Caribbean pine plantations showed strong linear relationships between $\delta^{13}C$ and $\delta^{15}N$ especially compared to tea plantations and mature forests (Fig. 5). We surmise that litter combustion through surface fires in these two land covers can change the natural abundance of N and C isotope ratio of soil, enriching $\delta^{13}C$ and $\delta^{15}N$, due to isotopic fractionation from volatilization and combustion (Huber et al., 2013; Hyodo et al., 2013). Most importantly, the strong relationship between C and N isotopes ratios indicates that soils under Kekilla fern and Caribbean pine may undergo similar soil microbial decomposition processes as compared to the other land uses. Both have foliage high in lignin, phenols, resins and tanins, recalcitrant ^{13}C-depleted substrates. In relation to microbial decomposition, Preston et al. (2006) viewed lignin as a paradox in C decomposition and $\delta^{13}C$ changes. Even though recalcitrant substrates are depleted with ^{13}C, since it decomposes slowly in soil, older soil C becomes more ^{13}C enriched at deeper soil depths.

While the mature rainforest showed relatively depleted $\delta^{13}C$ and $\delta^{15}N$ for both soil layers compared to other land uses, Caribbean pine plantations showed less ^{13}C depletion at 0–10 depth with a steep change to a ^{13}C enriched value at 10–20 cm (Fig. 3). Similar to our observations for the soils and organic matter (OM) of the mature rain forest, the ^{13}C depletion of the 0–10 cm depth in Caribbean pine is not surprising given the higher OM in the litter layer, with much of it coming from planted pine trees and mesic-loving, understory plants that have established beneath the pine canopy since planting (see Tomimura et al., 2012) (Table 1). The steep change of $\delta^{13}C$ depletion between 0–10 cm and 10–20 cm soil depths in Caribbean pine plantations can be substantiated by Cuevas et al. (1991) who compared above and belowground biomass production between secondary forest and Caribbean pine plantations in Puerto Rico. Their results found that the above ground biomass in the pine plantations was significantly higher than the secondary forest whereas fine root production in the pine plantation was relatively lower, and was mostly concentrated in the top 10 cm of the soil. Moreover, Wilcke and Lilienfein (2004) studied soil C replacement with land use conversion and demonstrated that C replacement under a 20 year old Caribbean pine plantation was only significant at the surface soil horizon (<15 cm) as compared to depths up to 2 m. We found similar trends and believe that the soils close to the surface of the pine plantations we studied were influenced by a regenerating shallow-rooted broadleaf understory. The SOC and the value of $\delta^{13}C$ close to the soil surface suggests a trend approaching the level of the mature rain forest; however, the deeper soil horizon in the pine plantations appeared to be significantly less influenced by the fine roots of the understory and were dramatically more enriched in $\delta^{13}C$ compared with the mature rain forest suggesting the legacy of past land use.

5. Management implications and conclusions

Tea plantations are a major agricultural land use throughout the tropics. After intensive cultivation, most of these lands have been abandoned and reverted to grass, shrub and fernlands. Many studies have emphasized the importance of understanding the impacts of forest conversion to agriculture and subsequent abandonment and reforestation on soil forming processes. Can reforestation be used to restore the productivity and fertility of soil? Can it be used to sequester carbon? What are the legacy effects of forest land conversion to agriculture post abandonment? As one of the significant restoration species planted at a global scale, Caribbean pine has been contentious species, which has different impacts depending on regions and climates. It has been a popular reforestation species in tropical Asia, yet studies on its impact on soil-forming processes have been non-existent.

Our study provides tentative answers to these questions. Our results demonstrate that the soils beneath Caribbean pine plantations and Kekilla ferns land show a strong legacy effect of fertilization from prior tea cultivation. In addition, we believe uncontrolled surface fires continue to influence these lands. However, there is also strong evidence that soils can recuperate in pine and fernlands through consistent inputs of litter and undisturbed processes of OM decomposition. There is also evidence that the post-establishment recruitment of other native rain forest trees within the understory of pine plantations may serve to increase microbial decomposition processes that facilitates reversion of soil structure and fertility to a status similar to that of the original forest.

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