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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