Does Forest Conversion to Tree Plantations Affect Properties of Subsoil Horizons? Findings from Mainland Southeast Asia (Lao PDR, Yunnan-China)

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Author contributions: CH designed the experiment and analysis data; XS carried out the data collection and sample analyses; SS provided information about location of the different land cover; AP, CH and XS analyzed interpreted the results. The manuscript was drafted by all the co-authors.

ABSTRACT

While forest conversion to tree plantations in northern Laos is ongoing since the 1990s, its impact on soil properties is yet to be assessed. Our objectives were (i) to assess changes in soil properties, including subsoil horizons down to 160 cm, in <14-year-old teak and 21-year-old rubber tree plantations compared to paired forest soils, in Luang Namtha province, Laos; (ii) review the recently published studies on the impact of tree plantations in neighboring Xishuangbanna, China; and (iii) to provide, based on (i) and (ii) broad recommendations for sustainable soil management in areas of northern Laos converted to tree plantations.

We analyzed selected chemical and physical properties of soil collected at 6 depths, from surface to a depth of 160 cm, along hillslopes, at the locations of 4 paired sites. All layers (0-160 cm) were very acidic pH (≤ 4.3) and depleted in exchangeable cations. Compared to their levels in the surface layer (0-10 cm), organic carbon content (21 g kg^{-1}) and specific pore volume (0.68 cm^3 g^{-1}) decreased by 62% and 44%, respectively at 40 cm, and by 81% and 53%, respectively at 110 cm. Forest conversion to tree plantations induced a decrease in pore volume and carbon content in the topsoil, but the subsoil remained unaffected. In rubber tree plantations, the nitrogen content dropped in all layers, including subsoil. In teak tree plantations, pH and phosphorus content increased in the deepest layers. Studies from

Xishuangbanna reported comparable degradations, also limited to the upper layers, following conversion to rubber tree plantations. Some isolated studies mentioned some apparent improvements of soil properties, related to textural differences.

Overall, the only significant subsoil degradation consisted in N depletion (0-160 cm) under rubber plantations. Even though the impact of forest conversion on soil properties, up to two decades following tree plantation, appeared limited to the uppermost soil layers, the observed alteration of soil porosity may have an impact on runoff and erosion, inducing irreversible degradation of soil functions and productive potential. The subtle nature of such changes hampers adequate perception of their actual importance by farmers and stakeholders who likely have the false impression that soils are unaffected by forest conversion to tree plantations. Consequently, an enforcement of soil conservation practices is recommended when establishing commercial tree plantations on the naturally nutrient-depleted and low porosity Acrisols of this region.

Key words: Acrisols, soil compaction, soil organic carbon, land use change, rubber tree plantation, teak tree plantation

Highlights

Our data come from an under-researched region and include subsoil (40-160 cm)

Only rubber plantations induced subsoil degradation (N depletion to 160 cm depth)

Degradation was mainly located in the top layer (0-20 cm)

Degradation consisted in increased bulk density and decreased carbon content.

Degradation may appear wrongly marginal in low fertility forested soils

1. Introduction

The forests of Northern Laos are hotspots of biodiversity of both global and local importance. In this landlocked country, a conjunction of factors including (i) a sparse population of shifting cultivation farmers, (ii) a rugged terrain, hampering the development of transport infrastructures and trade with the neighboring countries, and (iii) biodiversity legislation ((Ministry of Natural Resources and the Environment (MoNRE), 2016), contributed to the conservation of such natural environment (Lestrelin et al. 2012). Nevertheless, since the 1980s deforestation, land conversion, extractive activities, hydropower, and forest encroachment have impacted this environment; the pace of changes increased in the 1990s with the introduction of commercial plantations of teak (*Tectona grandis*) and rubber tree (*Hevea brasiliensis*). The characteristics of rubber tree expansion have been largely documented (Lu, 2017; Sayavong et al., 2020; Shi, 2008; Vongvisouk and Dwyer, 2016; Xiao et al., 2020). Tree plantations of Northern Laos were mostly established on sloping forested land, prone to soil erosion, due to shortage of lowlands already used for rice and vegetable cultivation (Brady, 1990; Singer and Munns, 1996). While such sloping land often bears conspicuous signs of erosion (gullies, landslides, etc.), more concealed forms of soil degradation (soil compaction, acidification, carbon loss, nutrient depletion, etc.) may also occur. The extent and rate of soil degradation (whether transient of irreversible) resulting from forest conversion to tree plantation appears highly context-dependent, influenced by baseline soil properties (i.e. as observed under forests), slope, climate, management practices, *etc*. (Vongsiharath, 2005). A comparative study by Sang et al. (2013) found that soil fertility of 17-year *Acacia mangium* plantations in Vietnam was similar to that of secondary forest and pasture. Ramesh et al. (2013) reported that, in uplands of Northeast India, 26-year-old *A. nepalensis* and *M. oblonga* plantations improved soil fertility. On the other hand, in the uplands of Luang Prabang province, Laos, severe soil erosion was observed in teak tree plantations without understory (Lacombe et al., 2018). Soil fertility loss was also observed in Hainan (China), following 41 years of continuous rubber tree plantation (Cheng et al., 2007).

While forest conversion to tree plantations in Luang Namtha may have lifted local populations out from poverty and improved both local and national economies, its environmental impact, particularly on soil resources, was not yet assessed when we undertook this survey. Such appraisal is increasingly needed as the rapid economic development of Laos will likely come at the cost of further deforestation, following a pattern similar to what previously happened a few decades ago in neighboring Xishuangbanna, southern China.

Xishuangbanna and northern Laos share common physiographic features including comparable geomorphology, climate, flora and fauna. The forested area of this Chinese province dwindled with promotion of extensive rubber tree plantations by the Government of China in the late 1950s (Li et al., 2007). With increasing pressure on the soil resources of Xishuangbanna, research focusing on soil properties in rubber tree plantations gained momentum: in the past 6 years, 16 papers focusing on different aspects of soils in forest and tree plantations of this region appeared in international peer reviewed journals, including research on soil physical degradation (Liu et al., 2018; Nespoulos et al., 2019; Zhu et al., 2018), soil organic carbon (Li et al., 2015; Liu et al., 2017; Sun et al., 2017; Yang et al., 2016), soil respiration (Goldberg et al., 2017; Wu et al., 2016; Zhao et al., 2018), spatial variability of soil characteristics (de Blécourt et al., 2017; Xia et al., 2016), soil improvement using intercrops (Chen, et al., 2019; Li et al., 2020; Liu C.-A. et al., 2018; Liu C. et al., 2018). It seemed interesting to take stock of all these results in order to verify whether there are general rules of evolution and whether they correspond to what can be observed in Laos.

In Northern Laos, given the potentially devastating environmental effects of wide-scale, poorly planned and managed conversion to tree plantations, both in terms of biodiversity (Bremer and Farley, 2010; Li et al., 2007), soil (Liao et al., 2012; Yuen et al, 2013) and water resources (Ziegler 2009), it appears essential to support an informed decision-making process through the provision of environmental data. In this perspective, our study aimed to: (i) measure selected soil and soil characteristics in forested areas (F), 12- to 14-year-old teak (T) and 21-year rubber plantations (R) of plots located in Luang Namtha province with a special attention to the subsoil layers; (ii) review recent literature on the impact of tree plantations in neighboring Xishuangbanna, China, in an attempt to identify regional trends and finally, (iii) provide broad outlines of recommendations for future development of tree plantations and agricultural practices in Northern Laos.

2. Materials and methods

2.1. Site description

The study sites were located in Luang Namtha province, Northern Lao PDR, which borders Yunnan province (China) (Fig. S1). Luang Namtha is a predominately mountainous area with an average elevation > 500 m a.s.l., and dominant sloping land. Average annual rainfall and temperature of the past 20 years were 1,450 mm and 23°C, respectively (Fig. S2). The main land uses on the sloping areas were firstly mixed secondary deciduous forest (F) and secondly tree plantations that mainly consist of rubber trees (R) and teak trees (T); in the lowlands the main crop was paddy rice (Fig. S1).

We initially sought paired plots (forest *v.s.* tree plantations) within micro-watersheds in order to minimize differences in the underlying pedo-climatic conditions of each pair. We succeeded to find only three sites (A, B, C) for which the three land uses (F, R, T) were located within the same watershed, at distances <5 km from each other, although with different slopes. We failed to find a fourth site that presented similar conditions, a difficulty frequently encountered in ecological/environmental studies (Davies and Gray, 2015). For the fourth site (D), each land use was located in a separate micro-watersheds, different from that where sites A, B, C are located, more than 5 km apart and on different slopes. The location of sites A, B, C and D are presented in Fig. S1 and their environmental characteristics are summarized in Table 1.

On the Lao soil map, soils at the sampled locations were described as Ferric Acrisols (sites A & C) and Ferric Alisols (sites B & D) (Table 1). The similarity of sites B and D in terms of soils offered some perspective to test the relative importance of pedological factors compared to climate and slope. The fact that three studied land uses were much more scattered at site D than at the three other site also provided a means to assess the importance of the paired plots approach in this context.

We selected teak and rubber tree plantations owned by smallholder farmers. Teak tree plantations, 21 years of age at the time of sampling, were found almost exclusively on gentle slopes (ranging 16-27%; Table 1), in places where forests had been cleared in 1995. Trees were randomly planted in 1996, with an average - but quite variable - spacing of about 2.5 m corresponding to an average tree density of about 2,000 trees per ha. Plantations had an approximate surface area of 2,000, 5,000, 5,000, 3,000 m^2 at locations A, B, C and D, respectively. During the first 3 years following tree planting, farmers intercropped young teak trees with upland rice, controlling weeds using hand tools. Following this early phase, weeds were simply slashed to minimize competition with growing teak trees.

The rubber tree plantations, 12 to 14 years of age at the time of sampling, were established on plots that had been cleared from 2003 to 2005. Unlike teak tree plantations, rubber trees were established on steep slopes (slope gradient ranging 50-77%; Table 1). The reason for this specific positioning of rubber tree plantations within the landscape is that all land with gentle slope nearby villages had already been used and only steeper and higher land, further away from villages, remained available (Sayavong *et al*., 2020). Lacking access to machinery, farmers laid out very narrow terraces that consisted of small flattenings (~0.3-0.5 m wide) cut by hand at regular intervals along the slope, following contour lines, resulting in minimal soil disturbance. Tree spacing was 2.5 m along tree rows with an inter-row distance of 4 m. Rubber tree plantations selected were 12,000, 7,000, 9,000 and 5,000 m^2 at plots A, B, C, D, respectively. During the first 3 years of the plantations, trees were intercropped with rice, without fertilization; weeds were controlled using hand tools. After the first 3 years, weeds and coppices were controlled by means of herbicide applications until complete rubber tree canopy closure. Farmers started to harvest latex when trees reached 7 years of age and at the time of this survey, the trees were still harvested.

Forest study sites were all located on steep slopes (ranging 51-74%; Table 1). Even if information about previous deforestation has to be taken with caution (Shi, 2008), the selected plots were described by local farmers as not having been deforested during at least 30 years. At plot A, forest (F) was a protected area of the village surrounded by rubber plantations. At plot B, F was part of the protected Luang Namtha catchment (set up for the provision of clean water to the town). Plots C and D were located within the boundaries of the Nam Ha National Protected Area, in relation with their protected status and recognized outstanding biodiversity (national protected area (NPA) since 1995; ASEAN Heritage Park since 2003; UNESCO–Lao 'Nam Ha Ecotourism Project' since 2006, awarded the 'Equator Prize' from United Nations Development Programme (UNDP).

2.2. Soil sampling

Soil samples were collected on two successive occasions: first, in rubber tree plantations and forests in January 2017 (i.e. middle of the dry season, Fig. S2), then in teak tree plantations in June 2017 (i.e. early rainy season, Fig. S2). Composite soil samples were collected at distance >= 2 m from a randomly chosen tree, at up-, mid- and low-slope positions, at least 3 collection points were thus pooled, depending on the length of the slope. At each sampling point, disturbed soil samples were taken using a standard auger at 6 soil depth increments: 0-10, 10-20, 30-40, 60-70, 100-110 and 150-160 cm, hereafter referred to as: 10, 20, 40, 70, 110 & 160 cm. Bulk density samples were collected using a soil core sampler with a core volume of 100 cm^3 (5 cm in diameter and height) at all but the deepest soil depth increment (i.e. at 0-10, 10-20, 30-40, 60-70, 100-110 cm). Following collection, soil samples were transferred to air-tight plastic bags to prevent evaporation of soil water. The number of soil samples could vary depending on study sites due to time and constraints needed to reach the sites, collect samples and bring them back to our vehicle (Table 1).

2.3 Soil analysis

Analyses were performed at the soil laboratory of the Department of Agricultural Land Management (DALaM, Lao ministry of Agriculture). Soil samples were oven dried at 105 °C for 48 h to determine soil dry bulk density (BD) and water content (WC). From bulk density we calculated the specific pore volume ($cm^3\ g^{-1}$):

$$\text{specific pore volume} = (1/BD) - 1/PD = (1/BD) - 0.377$$

BD is the bulk density ($g\ cm^{-3}$), PD is the particle density i.e. the volumetric mass of the solid soil particles that was assumed to be 2.65 $g\ cm^{-3}$ in the absence of high organic matter or oxide/hydroxides content.

Subsequently, dried soil samples were sieved through a 2 mm mesh and stored in sealed plastic bags for laboratory analysis according to standard methods detailed in Pansu et al. (2006). Soil pH was measured in 1:2.5 soil:water suspensions with a glass electrode pH meter (Jenway 3520). Organic carbon content (OC) was determined using the Walkley and Black method. Total nitrogen (N) was determined by Kjeldalh's method, while available phosphorus (P) was extracted following the Bray II method. Exchangeable potassium (K) was determined by extraction with neutral 1N NH_4OAc. Particle size analysis was carried out according to the pipette method after organic matter destruction using H_2O_2.

The soil organic carbon (SOC) stock was estimated using the equation:

$$\text{SOC (Mg ha}^{-1}\text{)} = 100 \text{ x BD x OC x thickness}$$

with 'BD' the soil bulk density (g cm^{-3} or Mg m^{-3}), 'thickness' is the thickness of the soil layer (m), OC in mg g^{-1}.

2.4. Statistical analysis

After having checked normality and homogeneity of variance, we applied ANOVA (Analysis of Variance), to compare the mean values of the soil properties (clay content, BD, WC, pH, OC, N, P, K, Ca), for each soil depth increment, considering the 4 sites A, B, C and D as replicates. This was done using R software 3.6.1 (R Core Team, 2020) and Agricolae package (Mendiburu and Yaseen, 2020).

3. Results

3.1. Soil organic carbon content

In forested areas, topsoil (0-10 cm) organic carbon (SOC) was 21 g kg^{-1} and decreased sharply with depth to 13 and 8 g kg^{-1} at 20 and 40 cm, respectively; in deeper layers, the SOC decreased at a lower rate, from 5 to 3 g kg^{-1} at 70 and 160 cm, respectively (Table 3). Compared to forested areas, in rubber tree plantations, only the topsoil (0-10 cm) displayed significantly lower soil carbon content (reduction of 5 g kg^{-1} compared to forest; $p<0.05$). In teak tree plantations, two layers were significantly affected: at 0-10 cm and 30-40 cm depth, the soil carbon content reduction compared to forest being 7 g kg^{-1} and 3 g kg^{-1}, respectively.

3.2. Soil bulk density

In forest plots, soil bulk density was low at the surface (average: 0.99 g cm^{-3}) and increased with depth (average: 1.44 $g.cm^{-3}$ at depth ≥ 70 cm; table 2). Such an increase in bulk density equates to a loss of more than half of the total pore volume (i.e. from 0.68 $cm^3.g^{-1}$ to 0.32 $cm^3.g^{-1}$). Compared to the forested areas, rubber tree plantations did not induce any significant change in soil density. In contrast, teak tree plantations significantly ($p<0.05$) increased soil bulk density of the uppermost soil layers: the porosity was reduced by 40% at 10 cm, 33% at 20 cm and 16% at 40 cm depth. Tree plantations also homogenized the soil at the surface compared to the forest: the coefficient of variation of porosity in the top layer was 32% and 16% under the forested areas and the tree plantations, respectively.

3.3. Soil acidity

All forest soils studied were strongly acidic, with pH ranging from 4.1 to 4.3 at all depth. Forest conversion to tree plantations did not have any significant impact on soil surface pH.

At depth, significant ($p<0.05$) differences were found only in teak tree plantations where pH increased (up to 4.5-4.8) at depths of 40 to 160 cm.

3.4. Plant nutrients

In the forested areas, N, P and K contents presented depth patterns similar to that observed for organic carbon, i.e. higher contents close to the soil surface with a steep decrease at 20 to 40 cm, and then a more gradual decrease down to 160 cm depth (Table 3). The C/N ratio decreased more regularly from 13 in the top layer to 6 at 160 cm. In contrast, exchangeable Ca as well as Mg and Na were low throughout the profiles, consistently with the observed acidic pH values, which under tropical climate, concur to induce nutrient leaching.

We only observed a significant ($p<0.05$) reduction in N content, along the whole profile, in places where forest had been converted to rubber tree plantations.

Conversion of forests to tree plantations did not appear to have impacted phosphorus profiles, as no significant differences were observed depth-wise between the phosphorus contents of the three land covers. In contrast, a significant decrease in potassium content was observed in the teak tree plantations, but only in the topsoil (-36% at 0-10 cm depth). Under rubber tree plantations the situation was different as a significant increase ($p<0.05$) was observed in two deep layers (+75% and +87% at 70 and 110 cm depth, respectively).

4. Discussion

4.1. Content and stocks of soil organic carbon

Soil organic carbon (SOC) profiles were similar to that reported for other tropical forests worldwide, i.e. with the highest contents observed in the top layer, a fast decrease in the upper layers (0-40 or 50 cm) and a slow decrease down to ≈150 cm, followed by very low but stable carbon contents over several meters (Ngo et al., 2013).

Tree plantations had an impact in the upper (0-10 cm) layer: SOC decreased in both rubber and teak tree plantations by 25 and 37% respectively, compared to forest, which probably related to differences in above ground biomass or litter production. In the 10-20 cm layer no significant difference was observed between forest, rubber and teak, while in the 30-40 cm layer, SOC under teak trees was significantly lower compared to forest and rubber; no difference was observed in the deeper layers. According to Cusack et al. (2018), fine root biomass is an endogenous factor controlling SOC, equally important as above ground or litter biomass. Lower fine root development under planted teak trees compared to rubber trees and forest could consequently explain such a localized difference.

In forested areas, the total soil carbon stock was 130.9 Mg ha^{-1} (table 4) approximately half of it (69.5 Mg ha^{-1}) being located in the 0-40 cm layer and 90 % in the 0-110 cm layer. Forest conversion to tree plantations decreased the carbon stock of the top layer (0-10 cm) but increased that of the 10-20 cm layer, a counter-intuitive contrast explained by the dramatic increase in bulk density in the 10-20 cm layer observed in tree plantations. Over the whole soil profile (0-160 cm), forest conversion to rubber tree and teak tree plantations decreased carbon stocks by 4% (~5 Mg) and 15% (~20 Mg), respectively. This is a much more limited reduction than that reported by van Straaten et al. (2015) who found that conversion of lowland tropical forest to cash crop plantations (including rubber trees) induced a loss up to one-half of the SOC, and that layers deeper than 1 m were affected. We also found that forest conversion to tree plantation did not alter the partitioning of the carbon stock: half being located in the 0-40 cm and half in the 40-160 cm volume. Our measurements of the impact of rubber tree plantations may be underestimated as the impact of slope cuts made to plant trees, which likely locally decreased SOC (Bruun et al., 2018), was not taken into account. Additional investigations should be conducted to assess whether future surveys should analyze separately cuts and undisturbed slopes.

4.2. Soil pH

pH is more sensitive to land use changes than clay for example, but in the absence of large chemical inputs, it varies slowly, especially in the deepest soil layers. A strongly acidic pH (4.1 to 4.3) was measured at all depths of the Luang Namtha forested areas which is in agreement with the characteristics of deeply weathered tropical soils. Such pH values less than 5.0 are known to induce aluminum toxicity (Kochian, 1995), which in turn can limit microbial activity and plant development (Fageria and Baligar, 2003). Compared to forest, no significant change was observed in rubber tree plantations, when in teak tree plantations a significant ($p<0.05$) pH increase was measured at 40 cm and deeper layers. This increase was approximately 0.5 pH unit and could result from soil sampling made at a different period compared to the forest and rubber tree plantations. The absence of acidification indicates that tree plantations did not accelerate leaching processes nor nutrient exports (Veldkamp et al., 2020).

4.3. Soil bulk density

In Luang Namtha, soils under forest or planted trees were characterized by an increase in soil bulk density with depth: from soil surface to 160 cm, the pore volume decreased by ≈ 50%. Such a reduced porosity could be surprising as, at the same time, the clay content increased by ≈ 30% and, all other parameters being equal, clay content and porosity are positively correlated as clay is structurally associated with high microporosity (Chaudhari et al. 2013). Thus, the decrease in the total porosity with depth is necessarily related to a decrease in macroporosity. This suggests a high and intense biological activity in the upper layers (macrofaunal and fine root density) and a dramatic decrease of this activity with depth (Lal, 1988). These two characteristics were indeed observed during our field observations and are consistent with observations made elsewhere (e.g. Nanganoa et al., 2019). Following forest conversion to rubber tree plantations, soil bulk density was unchanged; but in the case of conversion to teak tree plantations, soil bulk density increased in the upper layers (0-40 cm). This lower impact of rubber compared to teak trees may be related to age differences: in the plots that we studied, rubber trees being approximately 10 years younger than teak trees, a slow soil collapse due to decreased biological activity may only become detectable after sufficient time passed by. But it could also result in differences in soil macrofauna activity and fine roots development, the later being in agreement with reduced SOC content under teak tree plantations. More compact subsoil layers are generally considered as a hampering root development but in tropical forest those layers contribute to deep water storage and can play an important role in maintaining moist conditions in the root zone of the forest trees (Toriyama et al., 2013). Throughout southeast Asia, planted trees, have been observed to develop deep root systems in compact subsoils (Clément et al., 2019; Pierret et al., 2016). However, the dramatic decrease in soil macroporosity that we measured in the top layer has potential to drastically limit water infiltration and groundwater recharge, while increasing surface runoff and erosion, as observed in Luang Prabang.

4.4. Plant nutrients

Nutrient profiles were similar to SOC profiles, with the highest contents found in the top layer and a fast decrease with depth. Even in the top layer, nutrient contents were low, in agreement with very acidic pH values. The most striking impact of tree plantations was the decrease in N content observed from soil surface to 160 cm depth under rubber tree plantations and that seems strongly related to nitrogen uptake corresponding to latex harvesting. At the same time, a significant increase in K was observed under rubber plantations at 70 and 110 cm, which remains unexplained. The decrease in the K content at soil surface in the teak plantations is most probably related to a decrease in litter biomass.

4.5. Comparison between Luang Natham and Xishuangbanna

Our literature review indicated that soil types similar to those found in Luang Namtha (ALUPC, 2008) were also present in Xishuangbanna with a higher diversity as Alisols (Wu et al., 2016), Ferralsols (De Blécourt et al., 2014; Chen et al., 2019; Liu et al., 2018; Nespoulos et al., 2019; Sun et al., 2017) and Cambisols (Zhu et al., 2018, 2019). This similarity suggests that comparing the two regions is valid, at least in the perspective of a rough, preliminary assessment. Deeper knowledge of clay mineralogy (in particular the presence of high and low activity clays) should however be gained for a more detailed comparison, as this is a parameter known to influence many soil properties and functions (Veldkamp et al., 2020).

4.6. Content and stocks of soil organic carbon

In the forested areas of Xishuangbanna (Fig. 1 bottom left, Table S2), the average SOC value was >30 g kg^{-1} and decreased with depth; at 75 cm, values close to 0 were reported. The average SOC reported in the surface layers was higher than that we measured in Luang

Namtha. It is noteworthy that the range of SOC values reported in Xishuangbanna was considerable: in the topsoil (0-15 cm), the lowest and highest reported SOC were <30 g kg^{-1} (de Blécourt et al., 2013; Li et al., 2013; Liu et al., 2019) and >60 g kg^{-1}, respectively (de Blécourt et al., 2017 and Wu et al., (2016). In some cases, such discrepancies may arise from inconsistent reporting of analytical results, most probably expressed as 'organic 'matter' (SOM), i.e. SOC multiplied by a constant value of approximately 1.7; an hypothesis also confirmed by the excessively high C/N ratios reported in some papers (Wu et al., 2016). However, in other cases, SOC values remain surprisingly high, even if this potential reporting issue is accounted for: SOC of 35 and 38.6 g kg^{-1} were reported by de Blécourt et al. (2017) and Wu et al. (2016) respectively, i.e. 50 % higher than values reported by de Blécourt et al. (2013), Chen et al. (2019), Li et al. (2013) and Li et al. (2015) and nearly 100% higher than that of Liu et al. (2019). Such a large dispersion within a small region is quite puzzling as all soils have been similarly classified, and the composition and biomass of the forest trees and litter should not be significantly different. One possible explanation could be insufficient replication.

The literature about forest conversion to rubber tree plantations in Xishuangbanna does not indicate any general trend regarding its impact on soil carbon content (Chen et al., 2019; Liu et al., 2019; Goldberg et al., 2017; Li et al., 2013; Li et al., 2015), highlighting the need to document soil and environmental conditions as comprehensively as possible to enable interpretation of conflicting reports.

In the forested areas of Xhishuangbanna, Li et al. (2013) reported a stock of 33 Mg ha^{-1} in the 0-20 cm layer, i.e. a lower value than the 42 Mg ha^{-1} we found in Luang Namtha for the same soil depth range. In Luang Namtha, for the 0-40 cm layer, we found a value of ~70 Mg ha^{-1}, comparable to stocks of 61-63 Mg ha^{-1} in the 0-30 cm layer reported by Li et al. (2015) and Chen et al. (2019), but lower than values up to 117 Mg ha^{-1} reported by other authors (Yang et al. 2016, De Blécourt et al. 2013, De Blécourt et al. 2017). The wide range of carbon stocks values reported in Xishuangbanna (61 to 117 Mg ha^{-1}), while possibly reflecting extreme field variability, raises the issue of standardization and homogeneity of field and laboratory procedures, already pointed out nearly 10 years ago (Yuen et al., 2013) and still apparently unresolved.

A wide range of carbon stock values were also reported for rubber plantations of Xishuangbanna; the lowest stock being 47 Mg ha^{-1} (Liu et al, 2018), intermediate stock of ≈60 Mg ha^{-1} (De Blécourt et al, 2013, Li et al, 2020; Sun et al, 2017; Yang et al, 2016) and the highest stock being of 113.9 Mg ha^{-1} (Li et al, 2015), i.e. over twice the lowest stock. Only a few papers compared the carbon stocks under forest and tree plantations: some reports indicate a decrease associated with forest conversion to tree plantation (De Blécourt et al, 2013; Yang et al, 2016), while others did not find any change Chen et al. (2019), but also moderate to dramatic stock increases (Li et al., 2013; Li et al, 2015). This review on carbon stocks conducted in a small region, confirms that consistent conclusions and predictions of SOC and C stocks require a sufficient number of replicates and should be based on standard procedures of sampling as well as standard procedures of soil analysis.

4.7. Soil pH

In Xishuangbanna, all soil layers under forested areas were strongly acidic with slightly higher mean values compared to Luang Namtha (pH=4.7 to 4.8). In tree plantations, average pH slightly increased in deeper layers as was observed in teak tree plantations of Luang Namtha. It is noteworthy that several surveys reported a pH decrease in the top layer of tree plantations compared to that in forested areas (Liu et al., 2019; Goldberg et al., 2017; de Blécourt, 2014, 2017; Wu et al., 2016; Nespoulos et al., 2019; Li et al., 2013), even if they also mentioned a marginal pH increase at depth. Cation lixiviation from soil surface and accumulation in deeper layers could explain such characteristics. In both Luang Namtha and Xishuangbanna, pH changes induced by forest conversion to tree plantation appear limited and, anyway, insufficient to impact soil biological or geochemical functioning.

4.8 Bulk density

Bulk density values from Xishuangbanna forests are presented in Fig. 3 (top left) and table S1. It is noteworthy that, in most papers (i) data concerned the topsoil layers (0-20 cm) and there is a paucity of data below 50 cm, (ii) one or two depth increments only were investigated and (iii) different numbers of replicates were used to characterize different layers (Table S2). The linear regression of bulk density vs soil depth indicates that the lowest mean values are observed at the surface (1.05 g cm^{-3}) and increase with depth (1.3 g cm^{-3} at 75 cm). Even if the general trend is the same as in Lung Namtha, a wider range of values is observed in each layer, corresponding to three main patterns: (i) loose soil throughout the profile (M and B), (ii) compact soil throughout the profile (A, E, G and H), and (iii) intermediate bulk density throughout the profile (C and L). These differences could result from textural differences between different areas of Xishuangbanna but they could equally result from different analytical procedures. These large differences observed within a small region highlight the need for inter-site comparisons to ensure that standard procedures have been used.

In Xishuangbanna, conversion of forested areas to tree plantations increased soil bulk density in the upper layers (0 to ≈30 cm) when the subsoil remained unchanged (Fig. 3, top right), i.e. a trend similar to that observed in Luang Namtha, but with a larger diversity of situations. As in Luang Namtha, no heavy machinery was used, the increased bulk density following conversion to tree plantations probably resulted from a significant soil biological activity reduction. A few papers reported lower bulk densities following conversion to tree plantations (C, E, L down to 20, 15 and 50 cm, respectively). This apparent soil improvement could result from textural differences, i.e. more clayey horizons in the tree plantation areas (Nespoulos et al, 2019).

4.9 Nutrients

In the forested areas of Xishuangbanna, the few reported N contents were either similar (Zhu et al., 2019; Li et al., 2013) or much higher (Wu et al., 2016) than values we measured in Luang Namtha. For other elements, comparison between the results in Xishuangbanna and Luang Namtha were not possible because of the use of variable analytical methods in different surveys.

5. Conclusion

Overall, the results of our soil survey in Luang Namtha province, Laos, showed that (i) forest conversion to tree plantations mostly affected the porosity and carbon content of the topsoil and (ii) neither rubber nor teak tree plantations resulted in soil acidification. When considering the full 160 cm depth of the soil profiles, the decrease in carbon stocks compared to forest was lower in the rubber compared to the teak tree plantations: 4% (≈ 5 Mg) and 15% (≈20 Mg), respectively. Additionally, under rubber plantations, N was depleted throughout the whole soil profile (0-160 cm).

Our review of recent soil surveys in Xishuangbanna did not allow us to generalize our results: while general trends for some properties were similar in the two regions, published observations proved very diverse, difficult to compare and often contradictory; subsoil properties were rarely reported. Further studies on soil degradation in this area should therefore (i) be based on more standardized procedures (survey design, sampling depth, analytical methods, statistical analysis, etc..) , (ii) take into account pedo-geomorphological parameters that can have substantial impact on conclusions (clay content and type).

The limited level of soil degradation that we observed might be related to the fact that soils of the studied area are naturally very acidic, nutrient-depleted with a compact subsoil (i.e. with very few, if any, macropores). Our work is also indicative that time-scales to be considered to be able to detect changes in subsoil properties induced by land use change may be more than one or two decades. Nevertheless, the fact that we found that the most consistently predictable change in soil properties associated with forest conversion to tree plantations is, in the short term, topsoil compaction, is in itself valuable with regards to soil management practices. Indeed, such topsoil compaction is known to have major impacts on water balance and soil erosion, through decreased infiltration and increased runoff. Therefore, when converting forest to tree plantations, implementing practices that maintain topsoil porosity, such as, e.g. conserving a densely rooted and diverse understory and a healthy soil macrofauna, by means of agroforestry / intercropping designs, appears essential and were also strongly supported by several experiments recently conducted in Xishuangbanna.

Declaration of Competing Interest

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tables captions

Table 1. Location of the 4 sites and description of their position, main environmental characteristics and number of replicates for each of the 3 land cover (forest, rubber and teak tree plantations).

Table 2. Soil physical properties at 6 various depths and under forest, rubber tree and teak tree plantations in Luang Namtha district (Lao PDR).

Table 3. Soil chemical and physico-chemical properties at 6 various depths and under forest, rubber tree and teak tree plantations in Luang Namtha district (Lao PDR).

Table 4. Profiles of soil carbon stocks under forest, rubber and teak tree plantations.

Figure captions

Fig. 1. Xishuangbanna region soil properties: bulk density (top), pH (middle) and organic carbon content (bottom) at different depths, under forest (left) and tree plantations (right) in 16 recently published papers. The letter indicates the publication from which the data are coming from; the straight line is an estimate of the average trend (linear model) and the grey area represents the limit of confidence interval.

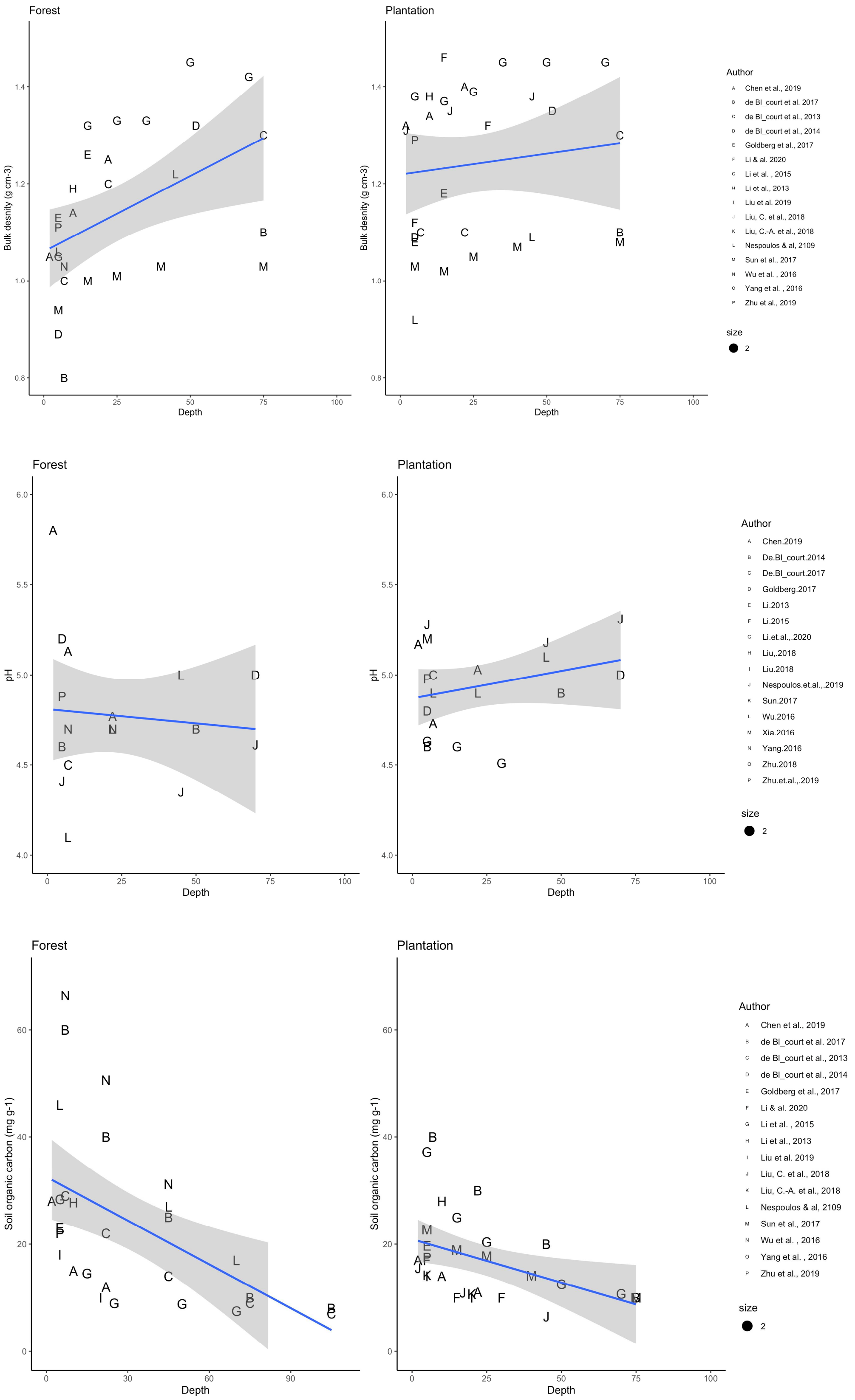

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Table 1. Location of the 4 sites and description of their position, main environmental characteristics and number of replicates for each of the 3 land cover (forest, rubber and teak tree plantations).

Sites	Village	Dist.* (km)	Dir.*	Soil type**	Slope (%)			Number of replicates		
					Forest	Rubber	Teak	Forest	Rubber	Teak
A	Phinhor	7	NW	Acrisols	74	77	20	6	9	4
B	Namdee	3	N	Alisols	64	65	16	3	3	4
C	Chalernsouk	12	W	Alisols	67	68	25	3	3	4
D	Sopsim	15	E	Acrisols	51	50	27	4	3	4

* Dist. : distance from the city of Luang Namtha until the village
** Soil type as indicated on Lao soil map

Table 2. Soil physical properties at 6 various depths and under forest, rubber tree and teak tree plantations in Luang Namtha district (Lao PDR).

	Depth (cm)	Clay (%)			Silt (%)			Sand (%)			BD (g cm^{-3})			Pore (cm^3 g^{-1})			WC (g g^{-1})	
		av	sd	cv(%)	av	sd	cv(%)	av	sd		av	sd		av	sd		av	sd
Forest	10	28	6	21	24	4	19	49	9	19	0.99	0.22	b	0.68	0.22	a	0.35	0.08
	20	33	8	24	22	4	20	45	11	23	1.11	0.17	b	0.54	0.13	a	0.30	0.06
	40	37	7	19	20	4	17	42	9	22	1.34	0.15	b	0.38	0.08	a	0.26	0.05
	70	40	8	19	18	4	21	42	11	25	1.44	0.13		0.32	0.06		0.25	0.06
	110	40	10	25	16	4	25	43	11	26	1.43	0.09		0.32	0.04		0.24	0.06
	160	36	12	35	16	4	26	48	14	30	-	-		*	*		0.20	0.06
Rubber	10	31	8	25	19	4	21	50	8	15	1.09	0.11	b	0.55	0.09	a	0.42	0.06
	20	36	9	24	18	4	25	46	7	16	1.21	0.11	b	0.45	0.07	a	0.34	0.05
	40	42	9	21	17	5	28	41	9	23	1.35	0.09	b	0.37	0.05	a	0.31	0.03
	70	45	10	22	16	4	25	40	9	23	1.41	0.07		0.33	0.03		0.30	0.03
	110	45	10	23	15	5	35	40	11	27	1.42	0.04		0.33	0.02		0.29	0.03
	160	41	13	32	15	3	24	44	13	29	-	-		-	-		0.26	0.05
Teack	10	34	15	45	28	5	17	38	17	44	1.29	0.12	a	0.41	0.07	b	0.32	0.06
	20	38	16	43	26	3	12	36	17	48	1.35	0.12	a	0.36	0.06	b	0.27	0.04
	40	40	19	46	22	3	13	35	18	52	1.43	0.04	a	0.32	0.02	b	0.26	0.05
	70	44	19	44	22	3	12	32	19	59	1.45	0.15		0.32	0.07		0.26	0.08
	110	43	19	44	23	6	24	34	19	55	1.47	0.19		0.31	0.09		0.26	0.07
	160	40	17	43	22	6	29	38	18	48	-	-		-	-		0.23	0.05

av is the mean value, sd the standard deviation, cv(%) is the coefficient of variation in percentage, n the number of replicates was presented in Table 1.
Different letters along the same column and at the same depth, indicate significant differences ($P<0.05$).

Table 3. Soil chemical and physico-chemical properties at 6 various depths and under forest, rubber tree and teak tree plantations in Luang Namtha district (Lao PDR).

	Depth (cm)	pH (1:2.5) av	pH sd		SOC (g kg^{-1}) av	SOC sd		N (g kg^{-1}) av	N sd		C/N	P (mg kg^{-1}) av	P sd		K (mg kg^{-1}) av	K sd		Ca (mg kg^{-1}) av	Ca sd	
Forest	10	4.34	0.61	ab	21.4	8.9	a	1.7	0.6	a	13	9.0	3.7		108	52	a	17	9	b
	20	4.33	0.48	ab	12.5	4.2		1.2	0.3	a	10	4.6	2.1		65	29		11	7	b
	40	4.09	0.1	b	8.2	2.3	a	0.9	0.2	a	9	2.3	0.7		52	29		6	3	b
	70	4.11	0.07	b	5.2	2.3		0.7	0.2	a	7	0.7	0.5	b	36	15	b	6	2	
	110	4.15	0.1	b	3.6	1.6		0.4	0.1	a	9	0.7	0.3	b	31	11	b	11	8	
	160	4.31	0.12	b	2.8	1.2		0.5	0.2	a	6	0.7	0.4	b	40	26		17	16	
Rubber	10	4.16	0.07	b	16.4	2.2	b	1.2	0.3	b	14	6.6	3.5		87	20	ab	12	5	b
	20	4.14	0.12	b	11.8	2.2		0.8	0.2	b	15	4.2	2.3		79	23		6	3	b
	40	4.14	0.11	b	8.0	1.4	a	0.5	0.2	b	16	1.6	0.8		68	16		6	3	b
	70	4.18	0.15	b	5.1	1.3		0.4	0.2	b	13	1.0	0.7	b	63	21	a	6	1	
	110	4.26	0.17	b	3.7	1.2		0.4	0.1	b	9	0.9	0.4	b	57	20	a	6	2	
	160	4.29	0.37	b	2.4	1.1		0.3	0.2	b	8	0.7	0.2	b	51	18		7	2	
Teak	10	4.49	0.24	a	13.5	2.9	b	1.4	0.4	ab	10	6.8	1.7		69	33	b	47	37	a
	20	4.48	0.45	a	10.7	2.0		1.0	0.3	ab	11	4.6	1.6		57	31		29	22	a
	40	4.45	0.43	a	5.4	2.8	b	0.7	0.3	a	8	2.4	1.3		39	16		13	9	a
	70	4.5	0.46	a	3.8	2.1		0.6	0.2	ab	6	1.7	1.3	a	39	15	ab	9	7	
	110	4.66	0.59	a	3.3	1.9		0.3	0.1	a	11	2.0	1.8	a	49	24	ab	13	12	
	160	4.83	0.69	a	2.7	1.5		0.3	0.1	a	9	1.5	1.0	a	34	10		9	7	

SOC is soil organic carbon.
av is the mean value, sd the standard deviation, cv(%) is the coefficient of variation in percentage, n the number of replicates was presented in Table 1.
Different letters along the same column and at the same depth, indicate significant differences ($P<0.05$).

Table 4. Profiles of soil carbon stocks under forest, rubber and teak tree plantations.

Depth	Thickness	Forest			Rubber			Teak		
(cm)	(cm)	per layer	cumul.	ratio	per layer	cumul.	ratio	per layer	cumul.	ratio
10	0.10	21.2	21.2	0.16	17.9	17.9	0.14	17.4	17.4	0.16
20	0.15	20.8	42.0	0.32	21.4	39.3	0.31	21.7	39.1	0.35
40	0.25	27.5	69.5	0.53	27.0	66.3	0.53	19.3	58.4	0.52
70	0.35	26.2	95.7	0.73	25.2	91.5	0.73	19.3	77.7	0.70
110	0.45	23.2	118.8	0.91	23.6	115.1	0.92	21.8	99.5	0.89
160	0.30	12.0	130.9	1.00	10.2	125.3	1.00	11.9	111.4	1.00

'per layer' indicates the stock for the layer of the thickness indicated in the second column; 'cumul.' is for the cumulated stock from the soil surface to the depth indicated in the first column; 'ratio' is for the ration between the cumulated value and the total carbon stock from soil surface to 160 cm depth.