Environmental Management (2012) 50:837–848
DOI 10.1007/s00267-012-9942-2

Soil Changes Induced by Rubber and Tea Plantation Establishment: Comparison with Tropical Rain Forest Soil in Xishuangbanna, SW China

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Received: 13 April 2011 / Accepted: 17 August 2012 / Published online: 18 September 2012

Abstract Over the past thirty years, Xishuangbanna in Southwestern China has seen dramatic changes in land use where large areas of tropical forest and fallow land have been converted to rubber and tea plantations. In this study we evaluated the effects of land use and slope on soil properties in seven common disturbed and undisturbed land-types. Results indicated that all soils were acidic, with pH values significantly higher in the 3- and 28-year-old rubber plantations. The tropical forests had the lowest bulk densities, especially significantly lower from the top 10 cm of soil, and highest soil organic matter concentrations. Soil moisture content at topsoil was highest in the mature rubber plantation. Soils in the tropical forests and abandoned cultivated land had inorganic N (IN) concentrations approximately equal in NH_4^+-N and NO_3^--N. However, soil IN pools were dominated by NH_4^+-N in the rubber and tea plantations. This trend suggests that conversion of tropical forest to rubber and tea plantations increases NH_4^+-N concentration and decreases NO_3^--N concentration, with the most pronounced effect in plantations that are more frequently fertilized. Soil moisture content, IN, NH_4^+-N and NO_3^--N concentrations within all sites were higher in the rainy season than in the dry season. Significant differences in the soil moisture content, and IN, NH_4^+-N and NO_3^--N concentration was detected for both land uses and sampling season effects, as well as interactions. Higher concentrations of NH_4^+-N were measured at the upper slopes of all sites, but NO_3^--N concentrations were highest at the lower slope in the rubber plantations and lowest at the lower slopes at all other. Thus, the conversion of tropical forests to rubber and tea plantations can have a profound effect on soil NH_4^+-N and NO_3^--N concentrations. Options for improved soil management in plantations are discussed.

Keywords Soil nitrogen · Rubber plantation · Tropical forest · Land-use change · Slope position · Environmental effect

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Introduction

Rapid population growth and economic development in tropical regions has continued to accelerate the depletion of natural resources, with large areas of tropical forests being converted to agricultural lands (Cayuela and others 2006; Steffan-Dewenter and others 2007). Between 1880 and 1980, the human population and the area of cultivated land across South and Southeast Asia increased by 262 and 86 %, respectively, while total forest cover decreased by 29 % (Flint 1994). During the period 1990–2005, approximately 60 % of oil palm expansion in Malaysia, and at least 56 % of that in Indonesia occurred at the expense of forests (Koh and Wilcove 2008). Land-use change has important consequences for the physical and chemical properties of soils, such as soil fertility, soil nutrient cycling with the atmosphere, and downstream aquatic ecosystems, because of changes in environmental conditions (Neill and others 1997; Templer and others 2005).

The conversion of natural forest into agricultural systems is often association with soil nutrient availability (Templer and others 2005). Hajabbasi and others (1997) reported that deforestation, and subsequently tillage practices in Lordegan region of Iran, resulted in bulk density increase, soil organic matter and total nitrogen decrease. Compared to the natural Cerrado savanna, continuous cropping and reforestation with pine led to a clear reduction of soil organic matter contents, whereas pasture and eucalyptus reforestation might have increased both the quantity and quality of soil organic matter (Neufeldt and others 2002). Land-use change can also indirectly affect microbial activity and C storage through its effect on soil organic matter quality and quantity (Templer and others 2005). Soil nitrogen and net mineralization rate are important indicators of soil fertility and nutrient cycling. Studies show that the rates of N mineralization and nitrification are higher in intact tropical forests than in agricultural lands (Piccolo and others 1994; Neill and others 1997; Templer and others 2005; Tripathi and Singh 2009). Reiners and others (1994) found significant changes in soil properties associated with conversion of forest to pasture including higher concentrations of NH_4^+-N, lower concentrations of NO_3^--N and lower rates of N-mineralization. Silver and others (2005)reported tropical plantations had lower rates of N cycling and increased potential for N loss compared to old-growth forests. The effects of land-use change on soil nutrient availability are of increasing concern, especially changes associated with the conversion of native forest into pasture (Neill and others 1995, 1997). Understanding the effects of converting forests for agricultural use on soil properties is very important, especially in Southeast Asia and China, where large areas of tropical forest have been converted to a variety of agricultural uses, such as rubber and tea plantations

Dramatic land-use change has occurred in Xishuangbanna, SW China, over the past 30 years (Li and others 2007). Xishuangbanna, being the most diverse region of China, is included in the Indo-Burma biodiversity hotspot (Myers and others 2000). It represents only 0.2 % of the area of China, but it contains approximately 5,000 species of higher plants (16 % of the nation's total), 102 species of mammals (21.7 %), 427 species of birds (36.2 %), 98 species of amphibians and reptiles (14.6 %), and 100 species of freshwater fish (2.6 %) (Zhang and Cao 1995). The ecological and socioeconomic context of Xishuangbanna is representative of other tropical regions of Southeast Asia that contain high levels of biodiversity and are threatened with deforestation and environmental degradation. Like many other tropical regions deforestation is occurring at high rates, and large areas of tropical forest and fallow land have been converted to rubber plantations in order to meet the growing demands of rubber products in the last decades. From 1976 to 2007, forest cover decreased from 69 to 45 %, while rubber and tea plantations increased from 1.3 to 11.8 % and 0.23 to 2.14 %, respectively (Li and others 2008).

The expansion of rubber plantation and its impacts on the environment in Xishuangbanna have received much attention by the local government and ecologists. Compared to primary tropical forest, rubber plantations with monoculture structure have less litter (Deng and others 2003), moreover, rubber plantations lacking understory vegetation cover cause higher soil loss (Fig. 1). The net N mineralization and nitrification rate is lower in rubber plantations and fallow lands than in the tropical forest (Sha and others 2000; Meng and others 2001; Li and Sha 2005). Although there has been some investigation into N dynamics in rubber plantations and tropical forests, there are few studies on the effects of tropical forest conversion to different-aged rubber plantations and tea gardens on spatial and temporal dynamics of soil N concentration in Xishuangbanna. Conversions of tropical forest or fallow lands to new rubber plantations are now taking place at high altitude and steep slopes. This is of concern because

Fig. 1 Photo of the rubber plantation (*left*) and the tropical forest (*right*)

land use and slope position can significantly influence distribution of soil nutrients and moisture (Fu and others 2004). There is an urgent need to improve soil quality by developing sustainable land-use practices, to reduce the rate of soil degradation and to ensure long-term sustainability of the plantation system in the study area. Recently, the local government proposed to build environmentally friendly rubber plantations, which aim at reducing water and soil loss and maintaining forest regrowth at a suitable slope. Understanding the effects of land use and topographic position on soil properties can help in guiding sustainable rubber plantation management and recovery of degraded-soil.

In Xishuangbanna, primary tropical forest, disturbed tropical forest and fallow land were the major land-cover types prior to the establishment of rubber plantations and tea gardens. Our objectives are to clarify whether there is a significant difference in soil properties from different-aged rubber plantations, tea gardens and abandoned cultivated lands compared with tropical forests, and to understand changes in the spatial and temporal dynamics of soil properties in the region.

Materials and Methods

Study Area

The study was conducted in Xishuangbanna (21°08′–22°36′N, 99°56′–101°50′E; 19,150 km^2), Yunnan Province, southwest China, which includes three counties (Jinghong, Menghai and Mengla), and borders Laos to the south and Myanmar to the southwest (Fig. 2). The region has mountain-valley topography with the Hengduan Mountains running north-south, and about 95 % of the region is covered by mountains and hills. The Mekong River flows through the center of Xishuangbanna, and the region contributes more than 20 important tributaries, resulting in many river valleys and small basins (Cao and Zhang 1997). The altitude varies from 2,430 to 475 m above sea level. The climate of this region is influenced by warm-wet air masses from the Indian Ocean in summer, including monsoons, and continental air masses of subtropical origin in winter, resulting in a rainy season from May to October, and a dry season from November to April (Zhang 1988). The combination of geography and climate in Xishuangbanna has created a transition zone between the flora and fauna of tropical South East Asia and subtropical and temperate China (Cao and others 1996), resulting in the most biodiversity region in China (Zhang and Cao 1995; Cao and Zhang 1997). The major land-use types in Xishuangbanna are: tropical forests, rubber plantations, tea gardens, fallow lands, and built-up areas.

Sampling sites were located in and around Menglun Town, Xishuangbanna (Fig. 2). The area receives a mean annual rainfall of approximately 1,500 mm, of which 80 % occurs in the rainy season (May–October), and the mean annual temperature is 21.8 °C (data from local meteorological station). The year is divided into two seasons: dry season (November–April) and rainy season (May–October) in study area (Zhang 1988). Furthermore, the dry season is divided into the foggy-cool season (November–February) and the dry-hot season (March–April). The sites used in this study were selected based on similarities in physical characteristics, parent material and past management practices. The experimental sites have a slope of 20–30° with slope length ranging from 150 to 200 m. The soils are classified as lateritic soil (Oxisol) developed from arenaceous shale sediments (Wang and others 1996).

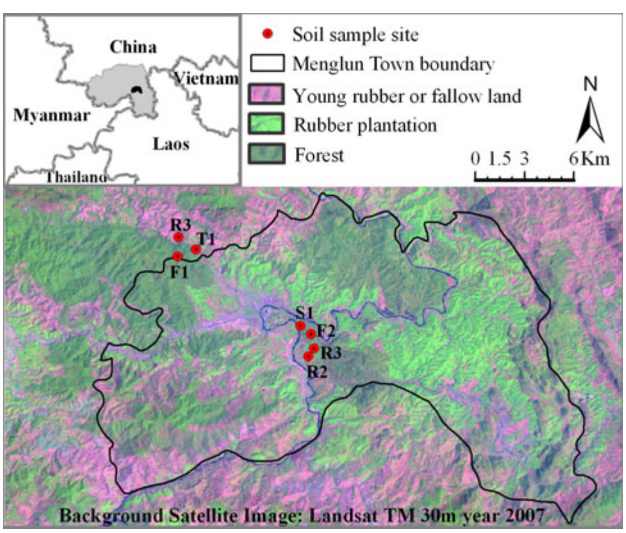

Fig. 2 Study area and measuring sites

Selection of Sampling Sites and Soil Sampling

Seven sites were sampled: an undisturbed primary tropical forest (intact forest), disturbed tropical forest (selective harvesting of trees until thirty years ago, but no evidence of recent human disturbance such as cutting and fires; this level of disturbance is typical for all but the remotest forest reserves in Xishuangbanna), 3-year-old rubber plantation (previously fallow land with one or two upland rice crops followed by fallow periods of 3–5 years, which was previously established on deforested tropical forest), 18-year-old rubber plantation (previously tropical forest), 28-year-old rubber plantation (previously tropical forest), tea garden (previously tropical forest) and abandoned cultivated land (long-term abandoned fallow land with high vegetation cover of shrubs and sparse trees for approximately 15 years, which was previously established on deforested tropical forest.). Locations of all the study sites were recorded using a global positioning system. Understory vegetation was cleared from the rubber and tea plantations with herbicide at least yearly since planting. A commercial fertilizer containing N, P and K was mixed into the soil in the 18-year-old rubber plantation (over approximately 10 years), 28-year-old rubber plantation (over approximately 20 years) and the tea garden (over approximately 15 years) twice a year. The rubber plantations were fertilized with mixed fertilizer (N, P and K) at a rate of approximately 40 kg N ha^{-1} $year^{-1}$. Fertilizers were point-applied in March and August at a dose of about 0.1 kg N per tree hole per year in the 18- and 28-year-old rubber plantations. The 3-year-old rubber plantation was not fertilized. The information listed above was from local rubber and tea plantation managers.

Seven sites were sampled between March 2008 and January 2009 to take into account seasonal variation. Soil samples were taken in March (dry-hot season), May (early rainy season), August (middle rainy season), October (later rainy season) and January (foggy-cool season).

Nine soil plots (at depths of 0–20 cm) were collected at each site (land-use type) to determine soil chemical and physical properties. Sampling plots were positioned at three representative topographic levels, namely, the upper, middle and lower slope of each site. Sampling locations were oriented along elevation gradients. Three replicates of soil sampling plots at 10 m intervals were taken parallel to the elevation contour at the same gradient slope. Each replicate consisted of three soil cores in composite, which were collected at random positions within 2 × 2 m plot and thoroughly mixed. Soil samples were taken up to 20-cm depth with a 4-cm diameter soil corer for soil texture, pH, soil organic matter, total N, NH_4^+-N and NO_3^--N determination. Soil bulk density samples at depths of 0-10 and 10-20 cm were taken with an impact driven bulk density sampler (2.5 cm radius, 5 cm liner) in March. There were a total of 63 soil sampling locations throughout seven different land-use types at each sampling time. Soil samples were placed in polyethylene bags to prevent water loss and were immediately stored in a cooler with ice for 24 or 48 h before laboratory analysis. The fresh soils were sieved through a 2 mm mesh screen to remove fine roots and rocks for further analysis.

Soil Measurements and Data Analyses

Soil moisture was measured with the Theta probe (Delta-T devices Ltd., England) under field conditions. Soil pH was determined potentiometrically at a 1:2.5 (soil:water) ratio in H_2O (National Forest Service of China 1999). Soil organic matter and total N were measured using the CN-analyzer (Vario MAX CN, Elementar Analysensysteme GmbH, Germany). Soil samples were shaken in 2 mol^{-1} KCl (soil:solution ratio = 1:10), centrifuged and passed through a rinsed GF/F filter, and the ammonium concentration was measured using the Indophenol blue colorimetric method (National Forest Service of China 1999). Nitrate concentration was determined using the spectrophotometric method with phenol disulfonic acid (National Forest Service of China 1999). Soil particle size analysis was carried out with the pipette method using sieved soil (<2.0 mm) (ISSCAS 1978). Bulk density samples were oven dried at 105 °C for 24 h and then weighed.

An analysis of variance (ANOVA) was used to test for differences of soil properties among land use, slope position and sampling season at the 0.05 significance level. To evaluate differences in soil properties (pH, soil organic matter and bulk density) across all sites mean data were compared using least significant difference. We specified an ANOVA model using the general linear model procedure to test the effects of land use and sampling season on soil properties (soil moisture, total N, inorganic N, NH_4^+-N and NO_3^--N) for all sites, and slope position and sampling season on soil properties of a single land use. All tests were conducted using the software SPSS v. 13.0 (SPSS 2004).

Results

Soil Properties in Response to Land Use

The domination textural class in all soils was clay loam (Table 1). The primary tropical forest and tea garden had sandy clay loam textured soils, the disturbed tropical forest silty clay loam, the 3- and 18-year-old rubber plantations and abandoned cultivated field clay loam, and the 28-year-old rubber plantation loam.

Soil bulk density from the top 10 cm for all sites ranged from 1.06 to 1.42 g cm^{-3} (Table 1). Bulk densities of the primary tropical forest ($P < 0.05$) and disturbed tropical forest ($P < 0.01$) were significantly lower than that of the other sites, and bulk density of the 18-year-old rubber plantation was significantly higher than that of the other sites ($P < 0.05$). Bulk density of the disturbed tropical forest from 10- to 20-cm depth was significantly lower than that of all three rubber plantations and the tea garden ($P < 0.05$). The primary tropical forest and the abandoned cultivated land also had lower bulk density than the rubber plantations and tea garden, but no statistically significant difference was found.

Soils from all the sites were acidic with pH 4.53–6.12 (Table 2). Soil pH was highest in the rubber plantations, especially, the 3-year and 28-year-old plantations ($P < 0.05$).

The average soil organic matter concentration (SOM) ranged from 22.79 to 36.57 g kg^{-1} across all sites

Table 1 Means and standard errors of soil particle size (at top 20 cm) and bulk density (at 0–10 cm and 10–20 cm) in seven land uses

Land use	Soil particle size (%)			Bulk density	
	2–0.05 mm	0.05–0.002 mm	<0.002 mm	0–10 cm	10–20 cm
F1	57.82 ± 2.35	21.93 ± 1.82	20.25 ± 1.30	1.16 ± 0.02	1.30 ± 0.04
F2	19.06 ± 1.75	46.60 ± 1.17	34.33 ± 1.09	1.06 ± 0.04	1.18 ± 0.05
R1	21.76 ± 2.63	43.41 ± 1.00	34.82 ± 1.80	1.27 ± 0.01	1.39 ± 0.01
R2	30.55 ± 0.66	38.66 ± 0.59	30.79 ± 0.40	1.42 ± 0.02	1.43 ± 0.01
R3	39.18 ± 3.14	33.78 ± 2.05	27.04 ± 1.38	1.29 ± 0.03	1.39 ± 0.01
S1	34.50 ± 1.50	33.17 ± 0.66	32.33 ± 1.97	1.26 ± 0.05	1.30 ± 0.06
T1	52.19 ± 1.41	24.04 ± 0.62	23.76 ± 1.62	1.27 ± 0.02	1.33 ± 0.03

F1 primary tropical forest, *F2* disturbed tropical forest, *R1* 3-year-old rubber plantation, *R2* 18-year-old rubber plantation, *R3* 28-year-old rubber plantation, *S1* abandoned cultivated land, *T1* tea garden

Table 2 Means and standard errors of soil properties (at top 20 cm) in seven land uses

Land use	Soil moisture (%)	pH	SOM (g kg^{-1})	TN (g kg^{-1})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	Inorganic N (mg kg^{-1})
F1	20.74 ± 0.76	4.53 ± 0.06	31.86 ± 1.08	1.77 ± 0.06	5.47 ± 0.49	6.56 ± 0.93	12.03 ± 1.18
F2	28.52 ± 0.72	4.95 ± 0.11	36.57 ± 1.40	2.07 ± 0.05	4.92 ± 0.47	7.87 ± 0.64	12.78 ± 0.95
R1	26.20 ± 0.62	6.12 ± 0.04	26.85 ± 0.63	1.94 ± 0.03	5.63 ± 0.34	3.72 ± 0.46	9.35 ± 0.44
R2	29.01 ± 0.70	4.96 ± 0.06	24.11 ± 0.45	1.45 ± 0.02	9.66 ± 0.52	0.78 ± 0.14	10.44 ± 0.56
R3	36.82 ± 0.32	5.10 ± 0.02	30.10 ± 0.55	1.70 ± 0.03	11.49 ± 0.43	0.81 ± 0.12	12.30 ± 0.45
S1	24.67 ± 0.68	4.81 ± 0.05	25.01 ± 2.11	1.68 ± 0.03	5.86 ± 0.32	6.71 ± 0.53	12.57 ± 0.66
T1	24.27 ± 0.57	4.83 ± 0.02	22.79 ± 0.53	1.40 ± 0.02	8.74 ± 0.52	1.32 ± 0.20	10.05 ± 0.60

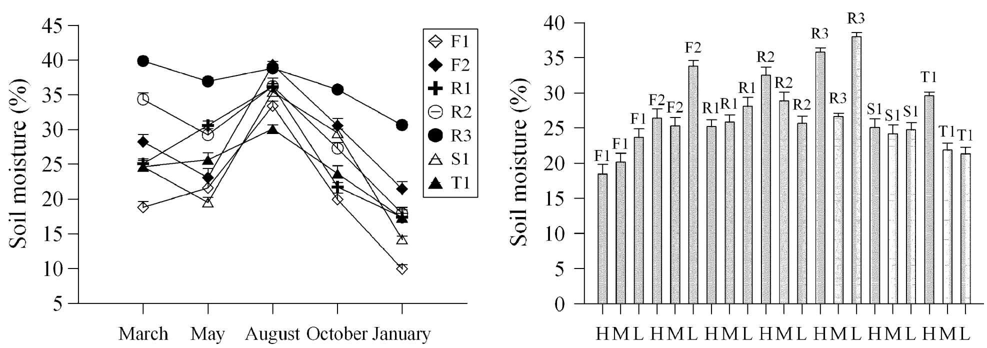

Fig. 3 Seasonal variation of soil moisture (*left*) and effect of slope position on soil moisture (*right*) in seven land uses (*error bars* represent standard error) (*F1* primary tropical forest, *F2* disturbed tropical forest, *R1* 3-year-old rubber plantation, *R2* 18-year-old rubber plantation, R3 28-year-old rubber plantation, *S1* abandoned cultivated land, *T1* tea garden, *H* upper slope, *M* middle slope, *L* lower slope)

(Table 2). The primary tropical forest, disturbed tropical forest and 28-year-old rubber plantation had significantly more soil organic matter than the other sites ($P < 0.05$). The average soil organic matter concentration was similar among the abandoned cultivated land, tea garden, 3- and 18-year-old rubber plantation, in which the values ranged from 22.79 to 26.85 g kg^{-1}.

The lowest average soil moisture content was found in the primary tropical forest (20.74 %), and the highest value was found in the 28-year-old rubber plantation (36.82 %) (Table 2). The moisture content was highest during the middle of the rainy season (August) and lowest during the dry season within all sites except for the 28-year rubber plantation, which showed little seasonal variation (Fig. 3). The decrease of soil moisture content after the end of the rainy season occurred more quickly in the primary tropical forest and abandoned cultivated land than in the rubber plantations and tea garden.

The average concentration of soil total N (TN) also varied among sites (Table 2). Total N concentration was higher in the two tropical forests than in the other sites except the 3-year-old rubber plantation. The disturbed tropical forest had the highest concentration of total N and the tea garden had the lowest concentration of total N. The

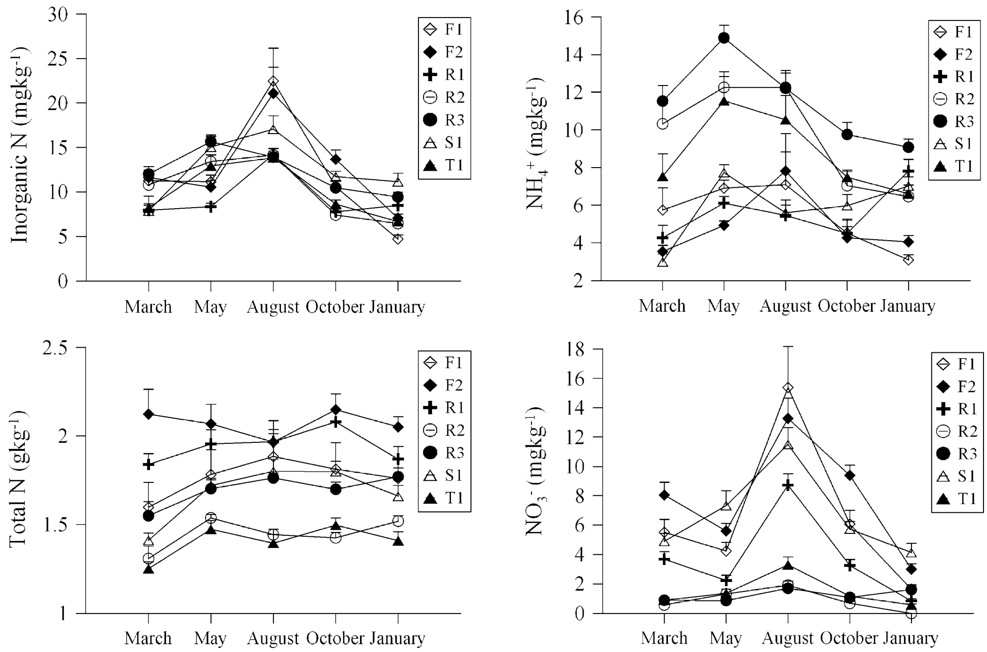

Fig. 4 Seasonal variation of soil properties (total nitrogen, NH_4^+-N, NO_3^--N, inorganic nitrogen concentration) in seven land uses (*error bars* represent standard error)

average concentration of soil total N ranged from 1.40 to 2.07 g kg^{-1} across all sites. Total N concentrations of the primary tropical forest, abandoned cultivated land and 3-year-old rubber plantation were slightly higher in the rainy season than in the other seasons, but no such seasonal change was found for the other sites (Fig. 4).

Results from ANOVA indicated that land use and sampling season were the main effects that significantly influenced soil moisture content and total N concentration, but interactions of land use with sampling season showed a significant influence only on the soil moisture within all sites (Table 3).

The two tropical forests and abandoned cultivated land had soil inorganic N concentrations that were relatively equal in NH_4^+-N and NO_3^--N concentrations, or with slightly higher NO_3^--N concentrations (Table 2). However, soil inorganic N pools were dominated by NH_4^+-N in all three rubber plantations and the tea garden. The NH_4^+-N concentration was higher in more disturbed sites (i.e., the tea garden, 18- and 28-year-old rubber plantations) than less disturbed sites (i.e., the two tropical forest and abandoned cultivated land). In contrast, soil NO_3^--N concentration was greater in the less disturbed sites. The seasonal dynamics of soil NO_3^--N concentration within all sites were characterized by an increase from dry to rainy season and reached its maximum value in August, followed by a gradual decrease in October and again in January (Fig. 4). The soil NO_4^--N concentration showed an increase from the dry to the rainy season within all sites. Furthermore, soil NO_4^--N concentrations reached a maximum in May within all sites, with the exception of the two tropical forests which reached a maximum in August (Fig. 4).

Table 3 Analysis of variance to compare the effects of land use, sampling season and their interactions on soil properties

	Source of variance		
	Land use	Sampling season	Land use × sampling season
DF	6	4	24
Soil moisture			
F	194.036	391.768	17.302
P	<0.001	<0.001	<0.001
TN			
F	46.671	6.597	0.921
P	<0.001	<0.001	0.573
NO_3^-			
F	47.814	47.934	4.993
P	<0.001	<0.001	<0.001
NH_4^+			
F	46.903	20.830	3.432
P	<0.001	<0.001	<0.001
Inorganic N			
F	7.236	61.855	4.513
P	<0.001	<0.001	<0.001

Average inorganic N concentrations were lowest in the 3- and 18-year-old rubber plantations, and tea garden (Table 2). The soil pool of inorganic N was almost identical in the 28-year-old rubber plantation, abandoned cultivated land and the two tropical forests. The seasonal pattern of inorganic N concentration was characterized by a high level in the rainy season, peaking in August within most sites, except the 18- and 28-year-old rubber plantations, where inorganic N concentration was highest in May (Fig. 4).

Results from ANOVA indicated land use, sampling season and interaction of land use with sampling season all significantly influenced the inorganic N, NH_4^+-N and NO_3^--N concentrations (Table 3). This means that on the different sampling dates, soil inorganic N, NH_4^+-N and NO_3^--N concentration responses generally differed depending on land use.

Soil Properties in Response to Slope Position

Soil pH was significantly higher at the lower slope than the other slope positions in the two tropical forests, abandoned cultivated land and 18-year-old rubber plantation ($P < 0.05$) (Fig. 5). The pH values were similar at the lower, middle and upper slope in the other sites. The average soil organic matter concentration was similar between the slope positions of a single site (Fig. 5). There were no statistically significant differences in soil organic matter between the slope positions within each site.

Slope position, sampling season and interaction of slope position with sampling season showed significant effects on soil moisture content within all sites, except the 3-year-old rubber plantation with showed no significant effects of interaction, and the abandoned cultivated land showed no main effect of slope position (Table 4). Mean soil moisture content in the two tropical forests, 3- and 28-year-old rubber plantations was higher at the lower slope than the other slope positions (Fig. 3). However, soil moisture content was higher at the upper slope than the other slope positions in the 18-year-old rubber plantation, abandoned cultivated land and tea garden.

The average soil total N concentration was lower at the upper slope than the lower slope in the two tropical forests, 3- and 28-year-old rubber plantation, but the opposite pattern was observed at the other sites. No significant interaction effect of slope position with sampling season was found for soil TN concentration of a single site (Table 4).

The average soil NH_4^+-N concentration within all sites was higher at the upper slope than the other slope positions

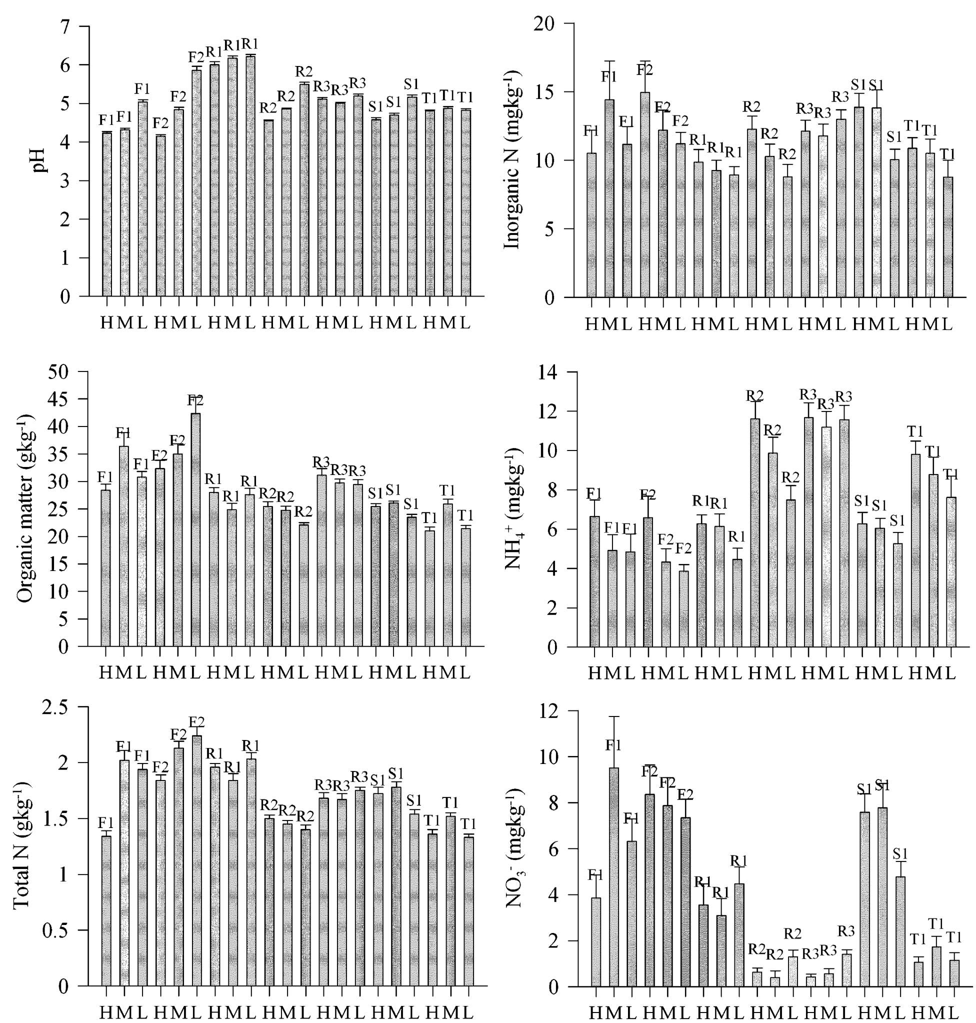

Fig. 5 Variation in soil properties (pH, soil organic matter, total nitrogen, NH_4^+-N, NO_3^--N, inorganic nitrogen concentration) along slope position in seven land uses (*error bars* represent standard error)

Table 4 Analysis of variance to compare the effects of slope position, sampling season and their interactions on soil moisture content and TN concentration

Source of variance	DF	Soil moisture		TN	
		F	*P*	*F*	*P*
Primary tropical forest					
Slope position (SP)	2	22.068	<0.001	27.429	<0.001
Sampling season (SS)	4	130.203	<0.001	1.324	0.284
SP × SS	8	5.097	<0.001	0.394	0.915
Disturbed tropical forest					
Slope position (SP)	2	90.688	<0.001	8.017	0.002
Sampling season (SS)	4	126.238	<0.001	0.585	0.676
SP × SS	8	7.369	<0.001	0.554	0.806
3-year-rubber plantation					
Slope position (SP)	2	3.741	0.027	3.848	0.033
Sampling season (SS)	4	191.456	<0.001	2.108	0.105
SP × SS	8	1.336	0.232	0.902	0.528
18-year-rubber plantation					
Slope position (SP)	2	33.131	<0.001	3.280	0.052
Sampling season (SS)	4	87.378	<0.001	7.072	<0.001
SP × SS	8	1.752	0.093	1.986	0.083
28-year-rubber plantation					
Slope position (SP)	2	11.874	<0.001	0.981	0.387
Sampling season (SS)	4	96.574	<0.001	2.541	0.060
SP × SS	8	4.543	<0.001	0.705	0.685
Abandoned cultivated land					
Slope position (SP)	2	1.311	0.273	15.674	<0.001
Sampling season (SS)	4	261.870	<0.001	15.412	<0.001
SP × SS	8	3.229	0.002	1.949	0.089
Tea garden					
Slope position (SP)	2	77.205	<0.001	12.397	<0.001
Sampling season (SS)	4	45.230	<0.001	6.236	0.001
SP × SS	8	2.522	0.014	0.205	0.988

(Fig. 5). The average concentration of NO_3^--N in the different-aged rubber plantations was higher at the lower slope than the other slope position. Average NO_3^--N concentrations in the primary tropical forest, abandoned cultivated land and tea garden were highest at the middle slopes. For the disturbed tropical forest, the slope pattern of NO_3^--N concentration was: upper > middle > lower. The average inorganic N concentration decreased from upper to downward slopes across all sites, with the exception of the primary tropical forest and 28-year-old rubber, which displayed the opposite pattern.

Results from ANOVA indicated that the interaction of slope position with sampling season significantly influenced inorganic N, NH_4^+-N and NO_3^--N concentrations in the primary tropical forest and disturbed tropical forest (Table 5). Furthermore, NO_3^--N concentrations differed significantly with slope position in the primary tropical forest, 18- and 28-year old rubber plantations and abandoned cultivated land, as did NH_4^+-N concentrations in the disturbed tropical forest, 3- and 18-year-old rubber plantations.

Discussion

Our results indicate that soil moisture content at the topsoil (0–20 cm) is higher in the rubber plantations than the tropical forests. This could be caused by a higher transpiration rate and consequently higher soil water withdrawal of the more densely vegetated forest in the tropical forest than in the monoculture rubber plantations (Giertz and others 2005). Moreover, increase in bulk density of the rubber plantations with human activities, such as trampling and weeding with herbicide may make the soil more compacted and reduce the formation of large pores. Reduction in porosity at the surface could induce serious reductions in infiltration and percolation, which will favor increase in surface runoff, soil erosion and ultimately serious land degradation (Giertz and others 2005).

Decrease in acidity with conversion of tropical forest to cultivated land (rubber plantation) is similar to reports on the conversion of tropical forest to pasture in the Atlantic Zone of Costa Rica (Reiners and others 1994). Yamashita and others (2008) also reported significantly lower soil pH in forests with high above ground biomass than in grasslands with lower above ground biomass, because of fewer exchangeable base cations retained in the soil by the translocation of base cations from soil to tree biomass in forest vegetation.

The variation of soil organic matter is complex, and is influenced by many factors such as soil texture, soil moisture and land-use type. Huang and others (2007) reported that soil with loamy or clayey textures had a high level of soil organic matter, but sandy or sandy-loamy soil had a low level of soil organic matter in an agricultural area in Yangtze River Delta region. In the present study, the soil organic matter concentration of the disturbed tropical forest, which is characterized by a higher percentage of fine particles, was higher than the primary tropical forest, which has a sandy clay loam soil. Soil in the tea plantation had a higher percentage of sandy particles and a significantly lower soil organic matter concentration compared with the other sites. Soil organic matter concentration increased with increasing wet conditions (Mclauchlan 2006). In our results, soil organic matter concentration of the 28-year-old rubber plantation, which has a high soil moisture content was significantly greater than that of the 3- and 18-year-old rubber plantations. Our data also indicated that soil organic matter concentration was highest in the primary and disturbed tropical forest. Clearly, tropical forests are able to

Table 5 Analysis of variance to compare the effects of slope position, sampling season and their interactions on soil NO_3^--N, NH_4^+-N and inorganic N concentration

Source of variance	DF	NO_3^-		NH_4^+		Inorganic N	
		F	*P*	*F*	*P*	*F*	*P*
Primary tropical forest							
Slope position (SP)	2	12.101	<0.001	2.272	0.121	2.796	0.077
Sampling season (SS)	4	23.368	<0.001	3.691	0.015	15.761	<0.001
SP × SS	8	2.340	0.045	2.585	0.028	2.184	0.050
Disturbed tropical forest							
Slope position (SP)	2	0.800	0.459	6.018	0.006	5.033	0.013
Sampling season (SS)	4	28.669	<0.001	4.862	0.004	22.080	<0.001
SP × SS	8	2.865	0.017	2.640	0.026	4.207	0.002
3-year-old rubber plantation							
Slope position (SP)	2	3.226	0.055	4.870	0.015	1.228	0.307
Sampling season (SS)	4	38.178	<0.001	5.795	0.001	25.738	<0.001
SP × SS	8	0.796	0.611	0.969	0.478	1.225	0.318
18-year-old rubber plantation							
Slope position (SP)	2	8.533	0.002	19.449	<0.001	17.373	<0.001
Sampling season (SS)	4	10.203	<0.001	20.977	<0.001	41.238	<0.001
SP × SS	8	1.990	0.129	1.098	0.392	1.403	0.236
28-year-old rubber plantation							
Slope position (SP)	2	11.027	0.001	0.209	0.812	1.341	0.277
Sampling season (SS)	4	8.306	0.001	10.113	<0.001	13.316	<0.001
SP × SS	8	2.582	0.063	0.849	0.568	1.015	0.446
Abandoned cultivated land							
Slope position (SP)	2	11.678	<0.001	2.356	0.112	13.638	<0.001
Sampling season (SS)	4	21.328	<0.001	16.657	<0.001	21.919	<0.001
SP × SS	8	1.767	0.124	1.223	0.320	2.311	0.056
Tea garden							
Slope position (SP)	2	2.568	0.099	1.845	0.176	2.034	0.148
Sampling season (SS)	4	9.766	<0.001	4.328	0.007	9.565	<0.001
SP × SS	8	0.985	0.459	0.537	0.819	0.636	0.741

produce heavy litter in maintaining the soil organic matter concentration. Lower soil organic matter concentration and higher bulk density in the rubber plantations, tea garden and abandoned cultivated land suggest that further incorporation of organic matter into the soil in the form of dead leaves, branches, and roots and development of fine roots will continue to decrease bulk density. This also suggests that the development of an understory in rubber plantations would help minimize soil exposure to erosion and nutrient leaching, and the establishment of multispecies plantations is encouraged.

The soil inorganic N concentration in the tropical forests and abandoned cultivated land had roughly equal concentrations of NH_4^+-N and NO_3^--N, or a slightly higher NO_3^--N concentration, while NH_4^+-N dominated soil inorganic-N pools in all three rubber plantations and the tea garden. A similar pattern in soil nitrogen transformation was observed in an Indian dry tropical forest that was converted to cropland, where nitrate-N decreased and ammonium-N increased (Tripathi and Singh 2009). Neill and others (1995) also reported that along the Rondonia transect in the southwestern Brazilian Amazon Basin NH_4^+-N and NO_3^--N pools were similar in forest soils and NH_4^+-N dominated pasture soil inorganic-N pools. Decrease in nitrate N and increase in ammonium N in the rubber plantations and tea garden may be related to a higher percentage of net ammonification rates, denitrification and fertilization. However, Li and Sha (2005) revealed that the net ammonification rates are much lower compared with mineralization and nitrification rates in the rubber plantations and tropical forest in Xishuangbanna. High soil moisture content, temperature (Liu and Li 1997) and bulk density of topsoil in the rubber plantations may induce high denitrification rates and more nitrate-N loss. Another reason may be that high rainfall results in a greater nitrate-N loss through soil erosion in rubber plantations and tea garden. The present study showed that the nitrate-N concentration was significantly less and ammonification-N concentration was significantly higher in the rubber plantations and tea garden, which are frequently fertilized, compared to the other, unfertilized, sites. According to Raison and others (1990), slow, steady inputs of N or repeated N additions could be favored by nitrifying bacteria to accelerate the nitrification process. Bengtsson and Bergwall (2000) also revealed that the NO_3^--N concentration increased by 40 % and the concentration of extractable NH_4^+-N increased by 3–10-fold in a plot receiving the largest amount of fertilizer compared with a control plot that was not fertilized. We think the plantation establishment systems with fertilization significantly influence soil NO_3^--N and NH_4^+-N concentrations, and would have further negative impacts on the environment. The high soil ammonification-N concentration in the rubber plantations and tea garden may be stimulating nitrifier activity, which in turn, would result in a greater nitrate-N leaching potential. Studying the effects of fertilization on the soil NO_3^--N and NH_4^+-N concentrations in the rubber plantations and tea garden will improve our understanding of these plantation systems and enable us to synchronize fertilizer applications with plant demands to reduce nitrate leaching or N_2O emissions to the environment after fertilization.

The soil properties of the 3-year-old rubber plantation and abandoned cultivated land, which had similar cultivation model before planting young rubber or abandoned, were not significantly different in soil NH_4^+-N and soil organic matter concentrations, but were significantly different in soil NO_3^--N and inorganic N concentrations. The lower NO_3^--N and inorganic N concentrations in the 3-year-old rubber plantation suggest that young planted rubber may be utilizing more of the soil stored N. This also indicates that fertilization of the rubber plantation should compose of synthetic fertilizers to improve rubber growth and production, nutrient availability and minimize N loss. Soil inorganic N concentration and distribution patterns between NH_4^+-N and NO_3^--N in the abandoned cultivated land was similar to that of the tropical forest. This indicates that after approximately 15 years the once cultivated land has accumulated soil nitrate- and ammonium-N in amounts comparable to the tropical forest. However, the accumulation of soil organic matter in the abandoned cultivated land has not approached magnitudes comparable to the tropical forests.

The seasonal pattern of soil inorganic N, NH_4^+-N and NO_3^--N indicate that concentrations were highest in the rainy season and lowest in the dry season in all sites. This coincided with the results of Meng and others (2001) where the highest NO_3^--N concentration was in the mid-rainy season and the highest NH_4^+-N concentration was in the early rainy seasons in a tropical forest and a rubber plantation. Li and Sha (2005) also showed that NH_4^+-N and NO_3^--N concentrations were high in the rainy season in a rubber plantation and forest land although no significant difference was detected for NO_3^--N concentration. Soil inorganic nitrogen values can show a positive relationship with soil temperature and moisture content (Mohamed and others 2007; Marcos and others 2007; Campos 2010). Frank and others (1994) revealed high soil moisture content induced high rates of N mineralization. Owen and others (2003) showed that the rate of nitrification was positively related to soil moisture content and N mineralization was positively correlated with nitrification rate. In the present study, high temperature and rainfall in the rainy season may be important factors related to high inorganic nitrogen concentrations.

A significant interaction effect of slope position with sampling season was seen for soil inorganic N, NH_4^+-N and NO_3^--N concentrations in the two tropical forest types, and no significant interaction was found for the rubber plantations, tea garden and abandoned cultivated land, suggesting absence of a considerable slope length could be directly associated with soil properties changes. Campos (2010) explained that slope lengths (ranging from 70 to 254 m) are not long enough to cause important changes in the microclimate that would significantly affect soil inorganic N content along a slope. However, in the present study, the significant differences of main effect of slope position were detected for NO_3^--N and NH_4^+-N concentration in the rubber plantations. The highest soil NH_4^+-N concentration was found at the upper slope in all study sites, while the highest soil NO_3^--N concentration was found at the lower slope in the rubber plantations and lowest soil NO_3^--N concentration at the lower slope at the other sites. Study on soil N transformation at different topographic levels in a Cryptomeria plantation showed ammonium-N was the dominant inorganic N at the ridge, while nitrate-N predominated at the foot of the slope (Tokuchi and others 1999). The study on a moist evergreen forest in Taiwan showed that the highest NO_3^--N concentrations were found at the lower sampling site and the highest NH_4^+-N concentrations were generally found at the upper location (Owen and others 2003). Tokuchi and others (1999) found soil solution chemistry was similar to throughfall at the ridge, but the soil solution with significantly high NO_3^- concentrations at the foot of the slope was different from throughfall, and suggested that the inorganic N form regulated not only N concentration but also cation concentrations. We think the spatial pattern of NO_3^--N and NH_4^+-N concentrations along the slope in the rubber plantations would have potential environmental implications that include greater N loss or leaching compared to tropical forests. In the rubber plantations, frequent fertilization at the upper slope would aggravate environmental problems. We suggest that rehabilitating tropical forests on the high and steep slope will not only reduce soil erosion but also restore soil nutrient and reduce environmental pollution. On the other hand, keeping a proportional area of forest regeneration on the upper slope as stepping stone fragments is also important for local biodiversity conservation.

Conclusion

We conclude that land-use change causes significant changes to soil inorganic N, NH_4^+-N and NO_3^--N concentrations, and that conversion of the tropical forest in Xishuangbanna decreased soil organic matter concentration and increased bulk density.

The tropical forests and abandoned cultivated land had inorganic N concentrations that were similar in NH_4^+-N and NO_3^--N concentrations, or a slightly higher NO_3^--N concentration, whereas soil inorganic N pools were dominated by NH_4^+-N in the rubber plantations and tea garden. The rubber plantations and tea garden, which are frequently fertilized, had significantly lower NO_3^--N and higher NH_4^+-N concentrations at the topsoil (0–20 cm) compared to the tropical forest and abandoned cultivated land. This suggests that fertilization of the rubber plantations should compose of synthetic fertilizers to improve rubber growth and production, nutrient availability and minimize N loss. We suggest that nitrate-N and ammonium-N concentrations are the critical indicators of soil health on different land uses after conversion from a tropical forest. Careful study of N dynamics in rubber plantations and tea gardens is required to synchronize fertilizer applications with plant demands to minimize the loss of nitrogen.

Tropical forest that has been converted into rubber plantations, tea gardens and abandoned cultivated land can result in changes to bulk density, and soil organic matter concentration, as well as soil compaction. Lower soil organic matter concentration and higher bulk density in these converted lands suggest that further incorporation of organic matter into the soil in the form of dead leaves, branches, and roots and development of fine roots will continue to decrease bulk density. This also suggests that development of the understory in rubber plantations would help minimize soil exposure to erosion and nutrient leaching. Accumulation of soil organic matter in the abandoned cultivated land has not approached magnitudes comparable to the tropical forest. This implies that the fallow land abandoned for approximately 15 years is sufficient to bring about substantial improvement in soil inorganic nitrogen, but recovery of soil organic matter is poor. The loss of soil organic matter and lack of decreased bulk density may hinder forest rehabilitation.

The highest NH_4^+-N concentration was found at the upper slope across all sites. The spatial pattern of NO_3^--N concentration showed a different trend with the lowest concentration at the upper slope in rubber plantations and lowest concentration at the lowest slope at the other sites. We suggest that impeding the development of unregulated rubber plantations and forest regeneration on steep and high slopes are important for the sustainable management of rubber plantations and minimization of soil nutrient loss.

Acknowledgments This work was funded by the National Natural Science Foundation of China (31170447 and 41271051). We are grateful to Liu MN and Li SA for their assistance in the field. We thank the Biogeochemistry Lab of Xishuangbanna Tropical Botanic Garden who provided help in soil analysis. We also thank Fu Y and Sha LQ for their helpful advice in methodological development. We appreciate our colleagues Li ZJ, Feng S, Wu JF and Xu WR for their help in soil sample collection. We also thank the editor and the anonymous reviewers for their valuable comments on the manuscript. We are grateful to Dr. Pelin Kayaalp for improving the language.

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