

## Linkages among land use, macronutrient levels, and soil erosion in northern Vietnam: A plot-scale study



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### ABSTRACT

**Objective:** This study examined the interrelations among vegetative cover and biomass, soil macronutrient levels, and soil erosion in northern Vietnam.

**Methods:** We selected ten dominant land-use types in a hilly area of western Hanoi including bare soil, agriculture (cassava or lemon grass), shrub land, five types of plantation forest, and indigenous forest. We measured the understory biomass, litter biomass, canopy openness, soil moisture content, soil pedestal height, soil hardness, soil bulk density, <sup>137</sup>Cs and <sup>210</sup>Pb<sub>ex</sub> activities, and soil carbon and nitrogen on three 1 m<sup>2</sup> plots for each land-use type. Soil erosion was calculated from both pedestal heights and radionuclides. Multivariate statistical analysis was used to identify the key factors controlling soil erosion and nutrient accumulations.

**Results:** Understory biomass ranged from 2 to 375 g m<sup>-2</sup>, and this tended to be higher in most of the forest types and shrubland than in cassava and lemon grass. In contrast, the amount of ground cover varied more by forest type than between the agricultural land uses and forest lands. The height of soil pedestals indicated that short-term soil erosion was negligible when understory biomass was greater than 130 to 150 g m<sup>-2</sup>. <sup>137</sup>Cs was only detected in the cassava plots, whereas <sup>210</sup>Pb<sub>ex</sub> indicated widely different erosion rates across the land uses, with lower values in the agricultural lands and two types of forest plantations, although this may be due to soil management practices. Both the correlation and principal component analyses showed that soil organic carbon and nitrogen were positively correlated to understory biomass and strongly and inversely influenced by bulk density. Soil erosion as indicated by soil pedestal height was strongly and inversely controlled by ground cover, litter, and understory biomass. Soil erosion was also heavily influential to soil chemical richness and bulk density.

**Conclusions:** Ground vegetation cover and the resultant soil erosion processes altered the production and accumulation of SOC, while forest cover did not always result in high soil fertility or low erosion. A simple characterization of forest or non-forest is not sufficient to calculate carbon and nutrient stocks, or assess erosion risk.

**Practice:** Understory biomass of at least 130 g m<sup>-2</sup> and high ground cover are essential for reducing soil erosion and sustaining short- and long-term soil productivity.

**Implications:** Rapidly developing areas in Southeast Asia, including hilly areas in North Vietnam, need to maintain understory biomass and ground cover for soil and nutrient conservation.

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### 1. Introduction

Soil erosion is a major environmental problem that threatens sustainable land use and is especially important in areas that are being converted from forests to agriculture or undergoing rapid development such as urbanization (Lal, 1990; Montgomery, 2007). Twenty-three percent of the Earth's land surface has been severely affected by soil

erosion, with an estimated 5–10 million ha being affected each year (Stavi and Lal, in press). Asia historically has had the highest percentage of degraded land at 31%, followed by Africa at 27% (Oldeman, 1994). The high proportion of degraded land in Asia is due to both rapid population growth and the associated land-use changes, combined with inadequate land-use planning and regulations to control soil erosion (Lal, 2004; Phan Ha et al., 2012; Quynh et al., 2005).

Soil erosion reduces soil productivity by decreasing soil macronutrients, such as nitrogen and phosphorus, and soil moisture storage capacity (Kuhn et al., 2009; Takenaka et al., 1998; Teramage et al., 2013). Soil

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erosion was reported to be the main mechanism for nutrient loss in areas devoted to growing cassava in the north central coastal region of Vietnam (Andersson, 2002; Maglinao et al., 2002; Podwojewski et al., 2008). In northern Vietnam, soil loss varies greatly with land use and location. The total soil loss in a 250-ha watershed covered by agricultural and forested land ranged from 16.3 to 172.2 g m<sup>-2</sup> year<sup>-1</sup> in Vinh Phuc province (Mai et al., 2013). Soil losses of 14 to 150 g m<sup>-2</sup> year<sup>-1</sup> were reported from Hoa Binh province (Phan Ha et al., 2012). Other studies reported soil losses of up to 1305 g m<sup>-2</sup> year<sup>-1</sup> in Hoa Binh province (Podwojewski et al., 2008) and up to 17,000 g m<sup>-2</sup> year<sup>-1</sup> for maize fields in Son La province (Tuan et al., 2014). These high soil loss rates will decrease land productivity, increase the need for chemical fertilizers, and contribute to regional biodiversity loss (Lal, 1998). High soil loss rates also can induce socioeconomic problems, including lower household incomes, food insecurity, and regional poverty (Ananda and Herath, 2003; Oldemal, 1994). Sediment delivery to streams and rivers can cause flooding and reservoir sedimentation as well as negative effects on water quality and aquatic resources (Chappell et al., 2004; Gomi et al., 2006).

Surface cover by litter or live vegetation is one of the important parameters controlling infiltration, surface runoff and erosion, and macronutrient levels (i.e., Nanko et al., 2008). Infiltration capacity generally increases with increasing density of understory vegetation (Hiraoka and Onda, 2012). The loss of ground cover due to deforestation, agriculture, over-grazing, and fires can lead to the formation of a soil crust, which results in increased overland flow and surface erosion (Larsen et al., 2009; Singer and Le Bissonnais, 1998). The presence of litter and understory vegetation also increases flow resistance, thereby reducing overland flow velocities (Tabacchi et al., 2000). In addition to providing litter and protecting the soil from erosion, understory vegetation also contributes to forest ecosystems through nutrient and carbon turnover during decomposition (Teramage et al., 2013) and facilitates increased rates of biogeochemical cycling (Yarie, 1980).

Monitoring erosion and macronutrient levels is difficult, particularly in rural areas of developing countries like Vietnam, because of the cost for regular sampling and the long time period needed to detect trends. These problems have led to the development of alternative methods for estimating soil erosion. Short-term erosion can be estimated by measuring soil pedestal heights (Okoba and Sterk, 2006; Sidle et al., 2004; Stocking and Murnaghan, 2001). A soil pedestal is a column of soil that is above an eroded surface because a rock or other object protected the underlying soil from rainsplash erosion. The difference in height between the top of the pedestal and the adjacent soil surface can be used to estimate storm or seasonal erosion rates (Sidle et al., 2004). Erosion rates over a few decades can be estimated by studying the distribution of radionuclides in the soil, particularly <sup>137</sup>Cs and <sup>210</sup>Pb<sub>ex</sub> (Navas et al., 2012; Walling and He, 1999). Both <sup>210</sup>Pb<sub>ex</sub> and <sup>137</sup>Cs are deposited from the atmosphere, and these radionuclides are rapidly adsorbed by organic matter and mineral topsoil. The distribution of <sup>210</sup>Pb<sub>ex</sub> with depth will reflect the erosion and deposition of soil. Similarly, the global fallout of <sup>137</sup>Cs provides a unique marker for evaluating soil erosion because deposition peaked in 1963 and then ceased. Comparisons of <sup>137</sup>Cs and <sup>210</sup>Pb<sub>ex</sub> between sites with similar soils but different land uses can therefore indicate how land use affects longer-term erosion rates (Li and Nguyen, 2010).

Although vegetation and litter cover are important controls on soil erosion and nutrient accumulation, interactions among vegetation, soil erosion, and macronutrient levels have rarely been investigated. Most previous studies have focused on the relationships between vegetation cover and soil erosion (Miyata et al., 2009; Mohammad and Adam, 2010; Zhou et al., 2008), or soil nutrient levels in relation to soil erosion (Kinderiene and Karcauskiene, 2012; Stolte et al., 2009), or between vegetation cover and soil nutrient levels (Fierer and Gabet, 2002; Yarie, 1980). However, the comprehensive interactions among land use, nutrient levels, vegetation and litter production, soil physical properties, and soil erosion have been rarely reported. An understanding

of these factors and their interactions for different land uses is important for sustaining short- and long-term ecosystem productivity (Angers and Caron, 1998; Lal, 2004; Schlesinger, 1990). The alternative to long-term and much expensive studies is to measure a more comprehensive suite of physical, chemical, and biological parameters across different land uses and then to apply multivariate analysis techniques. None of the previously-cited studies of soil erosion in northern Vietnam have provided this more comprehensive assessment of site factors and attempted to then analyze the various relationships among land use, vegetation, soil chemical and physical properties, and erosion.

Here, we hypothesize a strong linkage among soil nutrients, land use, and soil erosion in northern Vietnam, and that a simple characterization of land use may not be adequate to characterize soil nutrient status and erosion rates. Hence the objectives of this study were to: 1) characterize the vegetation and litter cover, soil physical properties, and nutrient levels in replicated plots with different land uses in northern Vietnam; 2) assess short- and long-term soil erosion using soil pedestals and radionuclides; and 3) evaluate the relationships and potential feedbacks between land use, macronutrient levels, physical soil properties, the amount of vegetation and litter, and soil erosion.

## 2. Methods

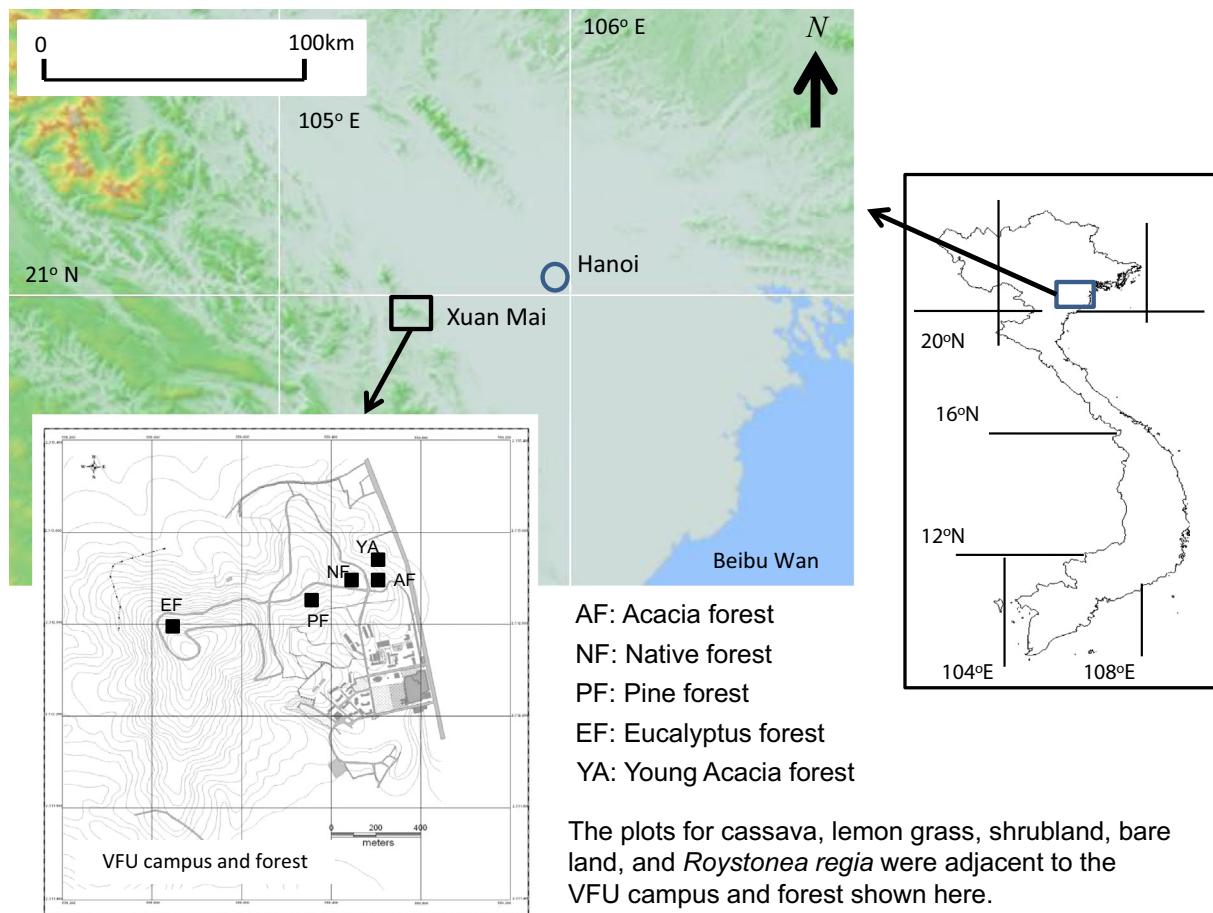
### 2.1. Study area and design

This study was conducted in and around Luot mountain (20°54'N, 105°34'E), which is adjacent to the campus of Vietnam Forestry University (VFU) in Xuan Mai town, Chuong My district, northern Vietnam (Fig. 1). The study area was about 110 ha and is dominated by ferrallitic soils. Seventy-five percent of the study area is hilly with complex topography that is relatively typical of northern Vietnam (Nhuan, 1996). Soil degradation is a major concern as a result of the land-use changes initiated by the rapidly growing population and associated economic development.

The study area ranges from 5 to 140 m above sea level and has a tropical monsoon climate. Average annual precipitation and temperature are 2268 mm and 23 °C, respectively, based on 20 years of data from the Kim Boi station located 18 km west of Xuan Mai. About 80% of the annual precipitation occurs during the rainy season from May to September. The underlying bedrock is largely porphyritic and the soil depth is approximately 1 to 2 m, although some areas have shallower soils. Humus content is typically 5–8%. The dominant land uses are agriculture and forestry, but population growth has caused the agriculture to change from shifting cultivation to more continuous cropping. Similarly, the native forests are often being replaced by plantations, and cutover forests – if not replanted-revert to shrubland dominated by *Eupatorium odoratum* and *Heliotropium indicum*.

Prior to the 1980s, the area was dominated by dense wild grass and shrubs mixed with local cultivation of cassava, taro, and maize. After VFU was established in 1984, various exotic forest plantations were established on a 129-ha hilly area. These include *Acacia mangium*, *Pinus massoniana*, and *Eucalyptus exserta*. In 1993 some indigenous trees also were planted, including *Elaeocarpus dubius*, *Aphanamixis grandiflora*, and *Dalbergia tonkinensis*. Many of the lands surrounding the VFU campus that are too steep or otherwise not suitable for growing paddy rice are now used for growing cassava (*Manihot esculenta*) and lemon grass (*Cymbopogon marginatus*).

This study focused on 10 major land-use types around VFU: (1) >20-year-old *P. massoniana* plantation, (2) >20-year-old *A. mangium* plantation, (3) 15-year-old forest of indigenous species (e.g., *E. dubius*, *A. grandiflora*), (4) >20-year-old forest dominated by *E. exserta* and *D. tonkinensis*, (5) 3-year-old forest composed of a hybrid of *A. mangium* and *Acacia auriculiformis* ("Acacia spp."), (6) agricultural land planted with cassava, (7) agricultural land planted with lemon grass, (8) shrubland, (9) bare land, and (10) 5-year-old ornamental

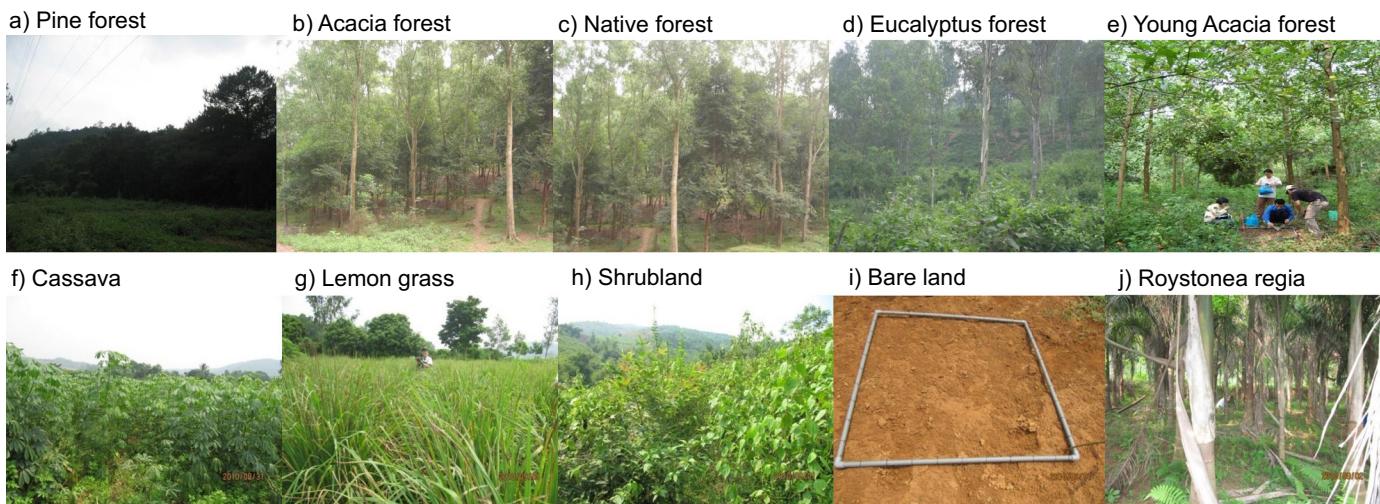


**Fig. 1.** Location of the study area and some of the forest types sampled in this study.

tree plantation (*Roystonea regia*) (Fig. 2, Table 1). In typical years cassava is propagated by cutting the stem into sections and planting in April, and harvested the following March. Lemon grass is a perennial crop and the leaves are most intensively harvested from mid-December to January. No fertilizer was applied to any of the plots used in this study. The cassava plots were probably subjected to plowing prior to planting, and the *R. regia* plots were in an area with small, crudely-built, sloping

terraces. By altering the slope length and steepness terracing can alter local runoff and other characteristics such as soil moisture (Chow et al., 1999).

The area to be sampled for each land use type was selected to be representative of the typical conditions based on local knowledge, and was selected to have similar lithology, soils, and climate. Once a representative land use type was selected, three plots were located from about



**Fig. 2.** Photos of each land use: a) *Pinus massoniana* forest; b) >20-year old *Acacia mangium* forest; c) native forest; d) *Eucalyptus exserta* forest; e) young *Acacia* spp. forest; f) cassava; g) lemon grass; h) shrub land; i) bare land; and j) *Roystonea regia*.

**Table 1**

List of land use types, dominant vegetation, duration of land use, slope, canopy openness, and surface cover. Values are means of three plots and values in parentheses are the standard deviation.

No.	Categories	Vegetation type	Duration of land use (years)	Slope (degrees)	Canopy openness (%)	Understory biomass ( $\text{g m}^{-2}$ )	Litter biomass ( $\text{g m}^{-2}$ )	Total ground cover (%)
1	<i>Pinus massoniana</i>	<i>Pinus massoniana</i>	>20	21 (14)	12 (4)	10 (9.7)	260 (75)	63 (15)
2	<i>Acacia mangium</i>	<i>Acacia mangium</i>	>20	11 (5)	14 (5)	115 (67)	180 (51)	76 (2)
3	Native forest	<i>Elaeocarpus dubius</i>	15	13 (9)	7 (2)	90 (93)	320 (70)	83 (4)
4	<i>Eucalyptus</i>	<i>Eucalyptus exserta</i>	>20	19 (8)	18 (3)	80 (34)	260 (97)	79 (12)
5	<i>Acacia</i> spp.	<i>Acacia mangium</i>	3	20 (6)	34 (7)	230 (54)	265 (100)	100 (0)
6	Cassava	<i>Manihot esculenta</i>	5	5 (2)	29 (11)	55 (20)	265 (140)	63 (28)
7	Lemon grass	<i>Cymbopogon marginatus</i>	10	4 (2)	59 (6)	65 (128)	115 (433)	79 (14)
8	Shrub	Various types of low shrubs	5–10	20 (2)	59 (6)	375 (63)	1020 (107)	91 (5)
9	Bare land	Not applicable	10	28 (9)	84 (0)	2 (2.8)	0	1 (1)
10	<i>Roystonea regia</i>	<i>Roystonea regia</i>	5	3 (3)	10 (4)	25 (22)	50 (44)	55 (23)

10–50 m apart in "typical" conditions. A random selection of land use types was not possible because of the need to obtain permission for sampling, to maintain close proximity and comparable conditions, and to avoid areas that had been fertilized or were otherwise not appropriate to the objectives of the study. Three 1 × 1 m plots were established for each land-use type because the primary goal of the study was to compare the variation among a wide variety of land uses rather than to conduct a more detailed sampling of a few land use types, and three plots were thought to be sufficient to identify the potentially large differences between land uses.

## 2.2. Field data collection and measurement of soil parameters

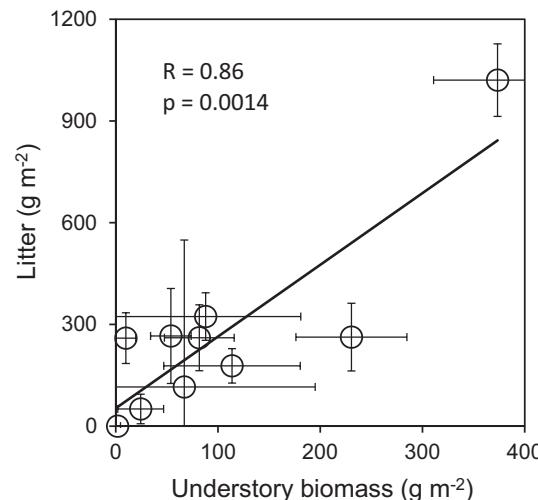
Field data were collected towards the end of the growing season in August–September 2010. In each plot we measured the overstory canopy cover, understory biomass, litter biomass, ground cover, and a variety of soil physical and chemical properties. Overstory canopy openness was measured from hemispherical photographs taken 50 cm above the ground surface with an 8-mm fish-eye lens using Gap Light Analyzer (Frazer et al., 1999). Understory biomass was measured by clipping all live leaves and branches from the ground surface to a height of 50 cm, and litter biomass was removed by hand. Both the understory biomass and litter samples were oven-dried for 12 h at 105 °C and weighed to obtain the dry mass. Ground cover by vegetation plus litter within the plots was calculated by a digital analysis of pictures taken from 50 cm above the ground using Adobe Photoshop CS (Chu et al., 2010). Mean slope was calculated from three measurements in each plot with a clinometer.

Soil pedestal height, soil hardness, and soil moisture content of the surface soil were measured at the end of rainy season in September at three locations in or immediately adjacent to the plots. Soil hardness (cm) was measured using a push-cone hardness indicator (Daiki Rika Kogyo, Saitama, Japan), and converted to pascals. Mean soil moisture content from 0 to 12 cm was measured at three locations in each plot using a CS620 Hydrosense probe (Campbell Scientific, USA). The mean height of three representative pedestals in each plot was assumed to represent the soil erosion during the May to August monsoonal rainy season (Sidle et al., 2004).

Two soil samples were taken from each plot. First, a bulk density sample of 5 cm in diameter from a depth of 0–5 cm was taken, and this was dried at 105 °C for 48 h to determine the dry mass. The second soil sample was taken in the center of each plot using a PVC cylindrical soil sampler that was 11.7 cm in diameter and 5.35 cm long, and this sample was used to determine soil texture as well as macronutrient and radionuclide concentrations. After air drying for a few days the larger pieces of organic matter such as roots were removed from this sample by hand. The particle-size distribution of the coarser particles was determined by dry sieving with meshes of 10.0, 5.0, and 2.0 mm. One gram of the fraction less than 2 mm was mixed with 6% H<sub>2</sub>O<sub>2</sub> and the clay, silt, and sand fractions were determined using a laser diffraction particle-size analyzer (SALD-3100, Japan).

The remainder of the fraction <2 mm was used to determine soil organic carbon (SOC), soil organic nitrogen (SON), and soil organic phosphorous (SOP) following Walkey (1947), Bremner (1996), and Kuo (1996), respectively. The resulting mean percent SOC and SON for each land use type were converted to C and N storage in grams per square meter using the area and depth of the soil sample and the mean bulk density.

Long-term soil erosion rates were estimated using two radionuclides, <sup>137</sup>Cs and <sup>210</sup>Pb<sub>ex</sub>. A representative fraction (<2 mm) of each dry sample was placed in a plastic pot for more than 20 days to achieve equilibrium conditions prior to analysis (Mizugaki et al., 2012; Pennock and Appleby, 2010). Each sample was analyzed with a high-resolution gamma-ray spectrometry system (GWL-120-15; ORTEC, Oak Ridge, TN, USA) coupled with a multichannel analyzer (EG&G MCA7600; SEIKO, Tokyo, Japan). The <sup>137</sup>Cs and <sup>210</sup>Pb<sub>ex</sub> concentrations in Bq g<sup>-1</sup> and Bq m<sup>-2</sup> were calculated following Pennock and Appleby (2010). In general, the continuous fallout of <sup>210</sup>Pb<sub>ex</sub> and the pulsed fallout of <sup>137</sup>Cs are rapidly and strongly adsorbed by clay minerals and organic matter, so the depth profile of Pb-210<sub>ex</sub> shows an exponential decline with depth and most of the measured Pb-210<sub>ex</sub> is in the top few centimeters (Wakiyama et al., 2010). Over time, however, the radionuclides can be mixed within the soil profile by biological processes such as earthworms or treethrow, or physical processes such as plowing or terracing. For a given site the total inventory of <sup>210</sup>Pb<sub>ex</sub> and <sup>137</sup>Cs will only change due to radioactive decay if there is neither erosion nor deposition (Zhang et al., 2006). While a complete inventory of radionuclides requires sampling throughout the soil profile, the high



**Fig. 3.** Relationship between the dry mass of litter ( $\text{g m}^{-2}$ ) and the understory biomass ( $\text{g m}^{-2}$ ). Circles indicate the mean of each land-use type, and the bars indicate the standard error of each land-use type.

**Table 2**

Mean soil texture, bulk density, soil hardness, water content, and pedestal height by land use type.

	Clay (%)		Silt (%)		Sand (%)		Soil bulk density (g cm <sup>-3</sup> )		Soil hardness (mm)		Soil water content (%)		Soil pedestal height (cm)	
	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>
<i>Pinus massoniana</i>	17.4	1.1	61.6	0.8	21.0	0.5	0.98	0.13	10.6	1.3	23.3	9.5	3.0	0.6
<i>Acacia mangium</i>	23.7	4.4	56.7	3.2	19.5	3.0	1.02	0.08	12.0	2.3	33.1	8.3	0.6	1.0
Native forest	20.2	1.5	59.1	1.4	20.7	0.6	1.02	0.04	9.7	3.8	29.4	1.7	0.0	0.0
<i>Eucalyptus</i>	13.4	3.5	63.6	1.9	23.1	1.7	1.14	0.15	10.6	4.6	25.9	6.0	0.0	0.0
<i>Acacia spp.</i>	14.9	6.1	63.0	2.6	22.2	3.5	0.86	0.08	7.9	3.4	17.6	3.3	0.0	0.0
Cassava	30.3	0.6	53.7	0.7	16.0	0.3	1.17	0.03	6.7	2.1	15.6	2.7	1.8	0.6
Lemon grass	13.2	2.3	61.1	1.0	25.7	1.6	1.00	0.03	15.8	0.7	44.7	4.4	0.0	0.0
Shrub	14.1	1.9	65.1	1.7	20.8	0.6	1.31	0.10	10.1	1.3	35.6	5.6	0.0	0.0
Bare land	19.1	4.4	55.4	3.1	25.5	1.5	1.02	0.12	15.2	0.9	32.4	2.0	3.3	0.2
<i>Roystonea regia</i>	17.7	2.2	58.9	1.4	23.4	1.2	1.18	0.06	13.2	2.2	50.4	2.5	1.1	0.3

<sup>a</sup> The standard deviation.

concentration of radionuclides at the soil surface means that our sampling from 0 to 5.35 cm should provide a reasonable approximation of the total inventory and a relative index of erosion rates among the different land uses. The surface inventory was calculated by:

$$I_s = CBdD_2d \quad (1)$$

where  $I_s$  is the surface inventory in  $\text{Bq m}^{-2}$ ,  $C$  is the radionuclide activity in  $\text{Bq kg}^{-1}$ ,  $Bd$  is the soil bulk density in  $\text{kg m}^{-3}$ ,  $D_2$  is defined as the percent of soil particles less than 2 mm in diameter, and  $d$  is the sampling depth.

The duration of individual land-use types was determined from field observations, local knowledge, and land-use classification using remote sensing. Forest age was generally estimated to be 25 years because the area around the VFU campus had been cultivated land or grassland prior to the establishment of VFU in 1984. The duration of agricultural land use was determined by analyzing LANDSAT Thematic Mapper (TM) images by LANDSAT-5 taken on 27 December 1993, 17 September 2000, and 8 November 2007. The resolution of the LANDSAT-TM images from visible to short wavelength infrared (bands 1 to 5) was 30 m. We applied an unsupervised classification with an iterative self-organizing data analysis algorithm using bands one to five (Yang, 2007). Topographic features such as ponds and road junctions around the VFU campus were used as geographical reference points. All of the image analyses were conducted using the Multi-Spec software package (Biehl and Landgrebe, 2002). Because some land classifications may appear to be similar to each other, we conducted a ground-truth calibration for land use types, particularly for the 2007 image. Images taken in 1993 and 2000 were ground-truthed by interviews with local people.

### 2.3. Statistical analysis

Pearson's correlation coefficients were calculated to characterize the relationships between the various vegetation and soil properties. Principal component analysis (PCA) also was used to identify the main factors controlling soil erosion and nutrient accumulations, and to reduce the number of soil-vegetation variables. Only components with eigenvalues greater than unity were selected to determine the main components. Variables with absolute eigenvector coefficients  $\geq 0.70$  were selected and considered significant in each component (Wotling et al., 2000). Multivariate statistical analysis was conducted using the SPSS software package (Ver. 19.0).

## 3. Results

### 3.1. Land use history, vegetation properties and soil characteristics

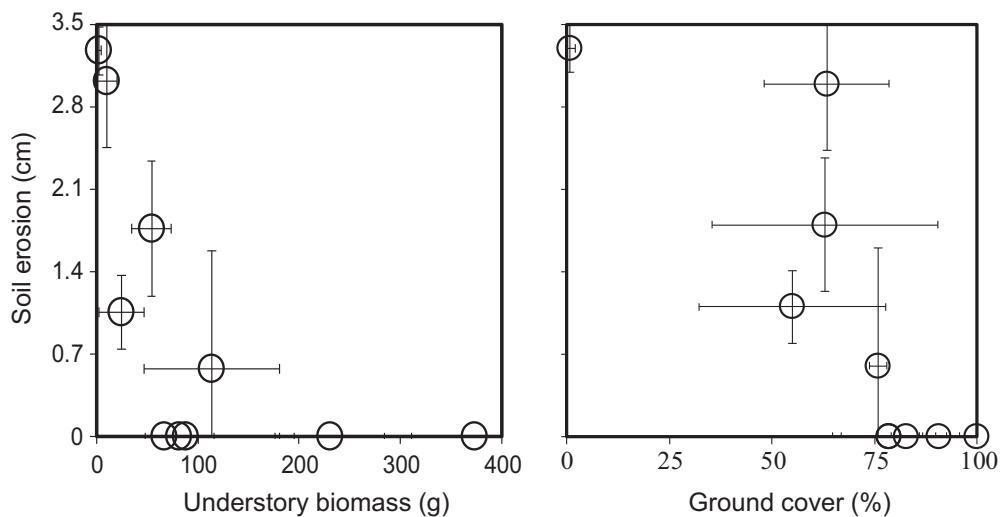
The remote sensing analysis indicated that the *P. massoniana*, *A. mangium*, and *E. exserta* forests around VFU had been present for more than 20 years (Table 1). The duration of other land uses ranged from 3 to 15 years (Table 1). Canopy openness ranged from 84% to 7%, with bare land having the highest openness followed by lemon grass and shrubland at nearly 60%, and then cassava and *Acacia spp.* at about 30%, and all the other forest types had less than 20% canopy openness (Table 1). Mean plot slopes were less than 5° for the agricultural and bare lands as well as the terraced *R. regia* plots, while the shrub and other forest land uses had mean slopes of 11 to 28° (Table 1).

Understory biomass ranged from 2  $\text{g m}^{-2}$  for bare land to 375  $\text{g m}^{-2}$  for shrubland (Table 1, Fig. 3). Forest and shrub lands generally had high understory biomass compared with agricultural land, except for

**Table 3**Mean soil organic carbon, organic nitrogen, C/N ratio, organic phosphorus, and  $^{210}\text{Pb}_{\text{ex}}$  values per kilogram and per square meter by land use type.

	SOC (%)		SON (%)		C/N ratio		SOP (%)		$^{210}\text{Pb}_{\text{ex}}$ ( $\text{Bq kg}^{-1}$ )		$^{210}\text{Pb}_{\text{ex}}$ ( $\text{Bq m}^{-2}$ )	
	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>	Mean	SD <sup>a</sup>
<i>Pinus massoniana</i>	3.18	0.19	0.19	0.01	16.6	0.4	0.24	0.03	116.1	16.9	5678	825
<i>Acacia mangium</i>	4.41	1.63	0.26	0.07	17.0	3.0	0.49	0.15	90.4	25.7	4632	1319
Native forest	3.41	0.27	0.20	0.01	17.1	0.4	0.30	0.20	84.0	31.9	4280	1625
<i>Eucalyptus</i>	1.98	0.31	0.13	0.04	15.4	0.8	0.09	0.01	82.4	19.5	4697	1112
<i>Acacia spp.</i>	4.79	0.47	0.29	0.03	16.4	1.5	0.40	0.09	45.5	17.6	1957	759
Cassava	1.92	0.06	0.12	0.01	15.7	1.3	0.19	0.14	42.3	3.6	2476	213
Lemon grass	5.17	0.72	0.27	0.00	19.1	1.1	0.33	0.02	39.0	11.9	1951	593
Shrub	2.48	0.22	0.16	0.01	15.5	1.8	0.44	0.06	77.4	22.2	5067	1453
Bare land	2.39	0.55	0.14	0.03	17.7	2.2	0.24	0.11	32.0	38.1	1634	1941
<i>Roystonea regia</i>	0.79	0.11	0.07	0.01	10.6	0.3	0.35	0.11	ND <sup>b</sup>	ND <sup>b</sup>	ND <sup>b</sup>	ND <sup>b</sup>

<sup>a</sup> The standard deviation.<sup>b</sup> Not detected.



**Fig. 4.** Relationship between soil erosion as indicated by soil pedestal height (cm) and a) understory biomass (g); and b) ground cover (%). Circles indicate the mean of each land-use type, and bars indicate standard errors.

*P. massoniana* and *R. regia*. *P. massoniana* had the lowest understory biomass at  $10 \text{ g m}^{-2}$  but similar litter biomass to the other forest types. *R. regia* also had very little understory biomass and litter. Litter biomass was highest in the shrubland at  $1020 \text{ g m}^{-2}$ , whereas the mass of litter in the forest plantations—except for *R. regia*—ranged from 180 to  $325 \text{ g m}^{-2}$  (Table 1). Understory dry mass and litter dry mass were significantly correlated, but this was largely due to the one point from the shrubland plots (Fig. 3).

Mean percent ground cover was highest in the shrubland plots at 91%, while ground cover in the forest plots ranged from 55% in *Roystonea* to 83% in the indigenous forest. Cassava and lemon grass had 63% and 79% ground cover, respectively, indicating no clear difference in ground cover between the latter stages of these crops and the various forest types (Table 1). Mean percent ground cover was correlated with understory biomass ( $r = 0.51$ ) and inversely correlated with canopy openness ( $r = -0.44$ ), but these correlations were not statistically significant.

Soil texture did not vary greatly among the land-use types, as percent silt plus clay was always at least 74% (Table 2). Lemon grass had the lowest mean clay content and the highest mean sand content, whereas cassava had the highest mean clay content and the lowest percent sand (Table 2). Notably, the bare land also had relatively high mean percent sand at nearly 26% (Table 2).

Soil bulk densities ranged from  $0.86$  to  $1.31 \text{ g cm}^{-3}$  with the highest bulk density being in the shrubland ( $1.31 \text{ g cm}^{-3}$ ), followed by *R. regia* ( $1.18 \text{ g cm}^{-3}$ ) (Table 2). Soil bulk densities in the forest land types ranged from  $0.98$  to  $1.18 \text{ g cm}^{-3}$ , with the highest density in the *R. regia* stands and the lowest in *P. massoniana* and *Acacia* spp.

Soil hardness was highest in the lemon grass and bare lands at more than 18 MPa. The forest and shrub lands generally had values below 11 mm except for the *Roystonea* plots at 13 mm and the *A. mangium* plots at 12 mm (Table 2). There was no clear pattern in mean soil water content between the plots (Table 2), and this can be attributed to the varying rainfall over the sampling period.

### 3.2. Soil organic carbon, nitrogen, and phosphorus

Measured SOC, SON, and SOP were relatively high in lemon grass, young *Acacia* spp. and *A. mangium* plots, whereas they were low in *E. exserta*, cassava, and *R. regia* plots, except for the normal SOP level in the *R. regia* plots (Table 3). The highest mean SOC was 5.2% in the lemon grass land, followed by 4.8% in *Acacia* spp. forest. *R. regia* had

the lowest SOC at 0.9%, and this can be ascribed to the disturbance due to terracing. Similarly, the highest SON was found in *Acacia* spp., lemon grass, and *A. mangium* plots at 0.29, 0.27 and 0.26%, respectively, while the lowest mean SON was in the *R. regia* plots (Table 3). *Eucalyptus* had relatively low SON and the lowest SOP at 0.09%, whereas the highest mean SOP was for *A. mangium* at 0.49%. Bare land also had low macronutrient values with 2.39% SOC, 0.14% SON, and 0.24% SOP. C/N ratios all fell between 15.4 and 17.7 except for the very low value of 10.6 for *R. regia* and the relatively high value of 19.1 for lemon grass due to its very high value for SOC (Table 3).

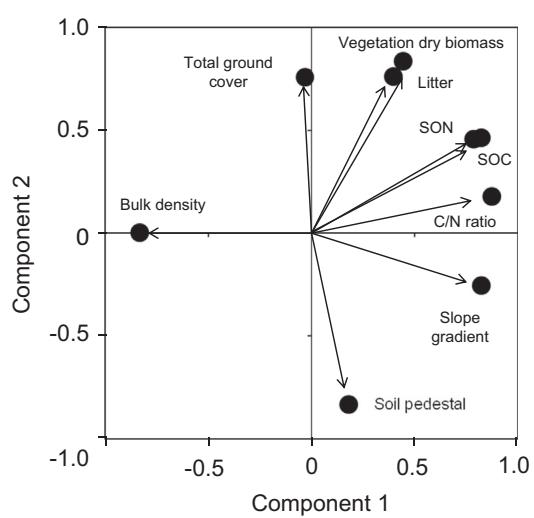
### 3.3. Soil pedestals and radionuclide concentrations

Soil pedestal heights varied from 0.0 to 3.3 cm (Table 2). Soil pedestals were highest in the mature *P. massoniana* forest (3.0 cm) and on bare land (3.3 cm) where the understory biomass and percent ground cover were both low (Fig. 4; Table 1). Soil pedestal heights were 1.8 cm and 1.1 cm in the cassava and *R. regia* plots, respectively, and both of these land uses also had relatively low values for understory biomass and percent ground cover (Table 1). In contrast, no soil pedestals were found in the indigenous forest, *Acacia* spp. forest, *E. exserta* forest, shrubland, or lemon grass; each of these land uses had relatively high percent ground cover (Tables 1, 2). A plot of soil pedestal height against understory biomass showed that the highest pedestals were associated with the lowest understory biomass and lowest percent ground cover (Fig. 4).

Measured  $^{210}\text{Pb}_{\text{ex}}$  varied from 0 to  $116 \text{ Bq kg}^{-1}$ , and this converts to 0 to  $5678 \text{ Bq m}^{-2}$  (Table 3). The concentration of  $^{210}\text{Pb}_{\text{ex}}$  generally was highest in the forest and shrub lands, and substantially lower in agricultural and bare lands (Table 3). *R. regia* had the lowest amount of  $^{210}\text{Pb}_{\text{ex}}$  (not detected), and this can be attributed to the terracing. The lower rates in the bare and agricultural lands are due to some combination of erosion, as indicated by the pedestal heights, and land disturbance, such as plowing. Within these broad groups there was no consistent pattern in the relationship between the amount of  $^{210}\text{Pb}_{\text{ex}}$  and percent ground cover, as the highest  $^{210}\text{Pb}_{\text{ex}}$  values were in *P. massoniana* and *E. exserta*, even though these two forest types did not have the highest ground cover (Tables 1, 3); *Acacia* spp. also had a relatively low mean  $^{210}\text{Pb}_{\text{ex}}$  value but 100% ground cover. Since measurable amounts of  $^{137}\text{Cs}$  were only detected in the cassava plots ( $3.2 \text{ Bq kg}^{-1}$  or  $159 \text{ Bq m}^{-2}$ ), the statistical analysis only used the  $^{210}\text{Pb}_{\text{ex}}$  values.

**Table 4**  
Correlation table for the physical and chemical characteristics measured in this study. Values in italics and bold are significant at  $p < 0.05$ .

	Understory biomass	Litter biomass	Canopy openness	Total ground cover	Soil hardness	Soil water content	Bulk density	SOC	SOP	C/N ratio	Clay content	Soil pedestal height	Slope	$^{210}\text{Pb}_{\text{ex}}$	
Understory biomass	—	.860	.202	.502	.207	.155	-.410	.780	.746	.279	.484	-.363	-.591	.199	-.151
Litter biomass	—	.114	—	.361	.270	.175	-.288	.627	.541	—	.541	-.208	-.379	.202	.002
Canopy openness	—	—	—	—	.451	.152	.056	.126	.050	.043	.428	-.252	.219	.411	-.346
Total ground cover	—	—	—	—	—	.174	-.008	.429	.508	.340	.011	-.260	-.818	-.387	.356
Soil hardness	—	—	—	—	—	.785	-.082	.101	-.002	.108	.166	-.323	.175	.380	-.305
Soil water content	—	—	—	—	—	.294	—	.127	-.183	.353	-.295	-.334	-.171	-.212	-.427
Bulk density	—	—	—	—	—	—	—	.697	.701	.074	—	-.511	.111	-.123	—
SOC	—	—	—	—	—	—	—	.987	.447	.759	—	.229	-.330	.441	.295
SOP	—	—	—	—	—	—	—	—	.679	—	.249	—	.373	.387	.317
C/N ratio	—	—	—	—	—	—	—	—	—	.501	—	-.150	—	-.279	-.027
Clay content	—	—	—	—	—	—	—	—	—	—	.364	—	-.018	.030	.644
Soil pedestal height	—	—	—	—	—	—	—	—	—	—	—	.364	—	.306	.031
Slope	—	—	—	—	—	—	—	—	—	—	—	—	.395	—	.021
$^{210}\text{Pb}_{\text{ex}}$	—	—	—	—	—	—	—	—	—	—	—	—	—	.139	—



**Fig. 5.** Ordination plot by principal components analysis. Components 1 and 2 represent 28% and 21% of the total variance, respectively.

### 3.4. Correlation and ordination

The correlation analysis showed a strong and significant positive correlation between understory biomass and the amounts of litter ( $r = 0.86$ ), SOC, and SON (Table 4). In contrast, the amount of litter was positively but not significantly related to SOC and SON. Bulk density was negatively correlated with SOC ( $r = -0.70$ ) and SON ( $r = -0.70$ ) as well as percent slope ( $r = -0.74$ ) (Table 4). Soil pedestal height and  $^{210}\text{Pb}_{\text{ex}}$  were not significantly correlated with any of the other variables, although SOC tended to increase with increasing  $^{210}\text{Pb}_{\text{ex}}$  (Figs. 5, 6).

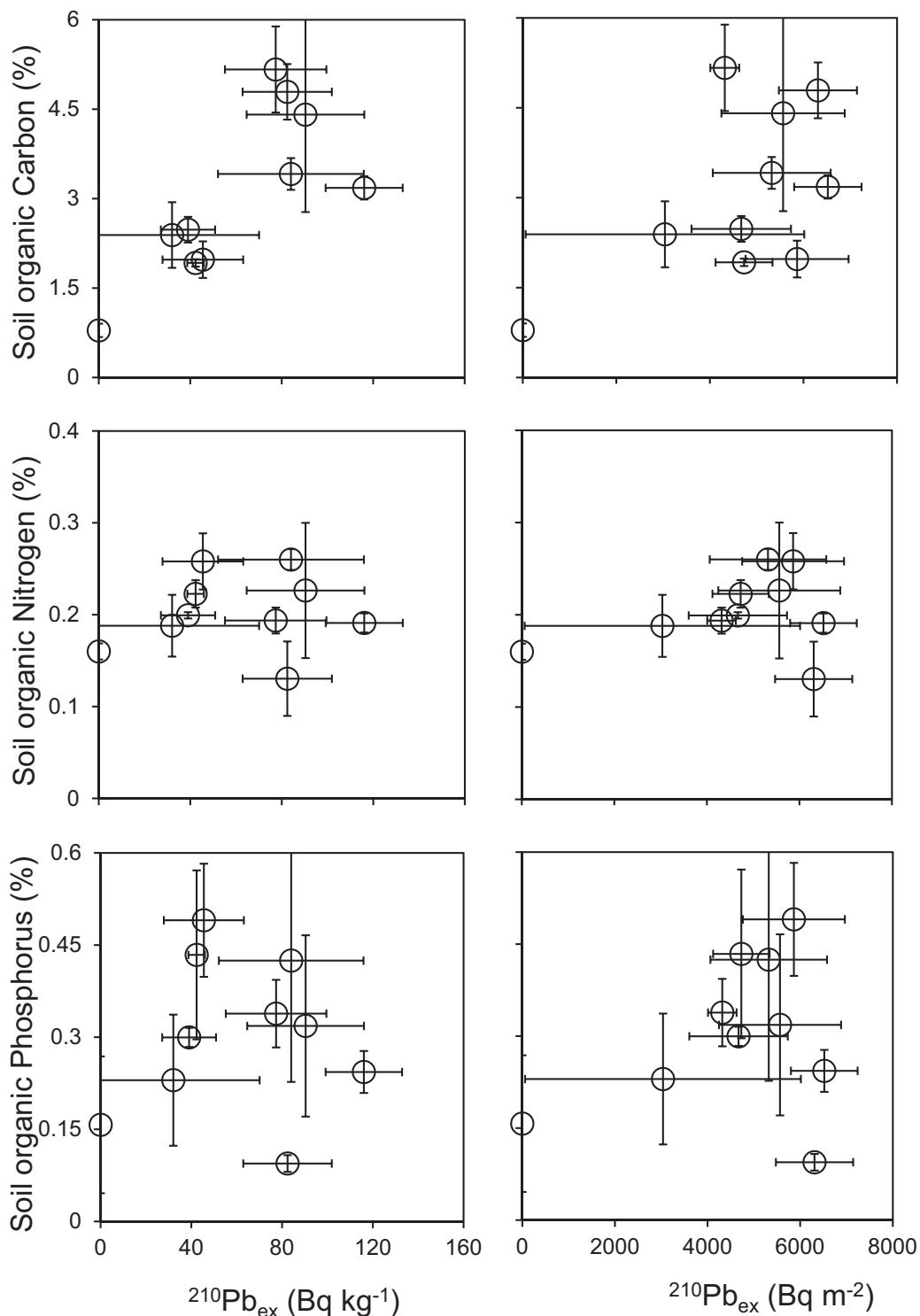
Five principal components explained 87.6% of the observed variation in the soil and vegetation data (Table 5, Fig. 5). The first component had high positive loadings for SOC, SON, C/N ratio, and slope, and a strong negative loading for soil bulk density (Table 5). This component reflects the soil chemical status and physical degradation due to terracing or cultivation, and it explained 28% of the total variance. The second component had positive loadings on understory biomass, mass of litter and total cover, and a negative loading on soil pedestal height (Table 5). This component is an indicator of soil cover and short-term soil erosion, and it accounted for an additional 21% of the total variance. The third component was dominated by  $^{210}\text{Pb}_{\text{ex}} (-0.79)$ , which was indirectly related to ground cover. The fourth and fifth components were dominated by clay content and total phosphorus, and each of these last three components explained between 11 and 16% of the total variance (Table 5).

## 4. Discussion

### 4.1. Interactions between understory biomass, litter, and soil properties

Understory biomass tended to be lower in agricultural land than most forest types, but both *P. massoniana* and *R. regia* had very low understory biomass. Like some forest types in Japan (Gomi et al., 2008; Hiraoka and Onda, 2012), these two forest types both had a relatively dense canopy that limits solar radiation and the growth of understory vegetation. *R. regia* also had relatively little understory biomass and also very low litter biomass, and this may be due to the fact that this was a relatively young stand. In contrast, the native forest (*E. dubius*) had the highest canopy cover, but still had a moderate amount of understory biomass and a high litter mass and ground cover.

Percent ground cover showed the expected positive relationships with understory biomass and litter and decreases with increasing



**Fig. 6.** Relationship between  $^{210}\text{Pb}_{\text{ex}}$  in  $\text{Bq kg}^{-1}$  and  $\text{Bq m}^{-2}$  and a) SOC, b) SON, and c) SOP. Circles indicate the mean of each land-use type, and the bars indicate the standard error.

canopy openness (Table 4). Hence these relationships were not significant due to the variation in forest ages and trade-offs between understory biomass and overstory openness. For example, *A. mangium* had a more open canopy but a higher understory vegetative biomass and the highest ground cover (Table 1). This shows how different forest types can vary greatly in the amount of canopy cover, understory biomass, and litter biomass, and that there are complex interactions between canopy openness, understory vegetation, the amount of litter, percent cover, and forest age. Even greater complexity is introduced by the variability in the agricultural crops, as cassava had less canopy

openness and therefore less understory biomass and less surface cover than lemon grass, but it had much more litter biomass (Table 1). Shrubland tended to be intermediate with not only high canopy openness but also high understory and litter mass, resulting in more than 90% ground cover. This makes simple generalizations difficult, except for bare land having very little overstory, biomass, and percent cover.

Soil organic carbon and nitrogen were most strongly correlated with understory biomass rather than litter biomass or ground cover (Table 3). Litter biomass was much more closely correlated with understory biomass than canopy openness (Table 4), and the combination of

**Table 5**

Results of PCA. Variables underlined with absolute eigenvector coefficients  $\geq 0.70$  are considered significant.

	Rotated component matrix				
	Component				
	1	2	3	4	5
Understory biomass	0.443	<u>0.836</u>	0.242	0.118	0.124
Litter biomass	0.396	<u>0.761</u>	0.242	0.137	-0.168
Canopy openness	0.282	-0.068	0.681	0.151	-0.096
Total ground cover	-0.034	<u>0.758</u>	-0.597	-0.021	0.221
Soil hardness	0.156	-0.130	0.649	0.653	0.127
Soil water content	-0.356	0.095	0.505	0.613	0.384
Bulk density	<u>-0.836</u>	0.002	0.052	0.026	-0.080
Total carbon	<u>0.820</u>	0.465	-0.061	0.031	0.323
Total nitrogen	<u>0.782</u>	0.459	-0.163	0.004	0.381
Total phosphorus	<u>0.080</u>	0.152	0.009	0.040	0.966
C/N ratio	<u>0.870</u>	0.178	0.087	-0.036	-0.133
Clay content	-0.096	-0.284	0.064	<u>-0.875</u>	0.069
Soil pedestal height	0.180	<u>-0.833</u>	0.247	-0.154	-0.237
Slope	0.821	-0.256	0.155	0.295	-0.318
$^{210}\text{Pb}_{\text{ex}}$	0.350	-0.093	<u>-0.790</u>	0.107	-0.063
Eigenvalues	4.17	3.21	2.37	1.75	1.64
Variance (%)	27.8	21.4	15.8	11.7	10.9
Cumulative explanation	27.8	49.2	65.0	76.7	87.6

higher litter and understory biomass can produce more soil nutrients via decomposition processes. Soil bulk density was significantly and negatively correlated with soil nutrients (Table 4), and again the variability among forest types is striking. For example, *Acacia* spp. has a high SOC (4.79%) and a very low bulk density of  $0.86 \text{ g cm}^{-3}$ , whereas *R. regia* has a low SOC (0.79%) and a high soil bulk density of  $1.18 \text{ g cm}^{-3}$  (Table 2).

The first axis in the principal component analysis clearly showed the strong contrast between bulk density and soil macronutrients, and the inverse relationship between soil macronutrients and bulk density can be explained in part by the increase in soil microbial activities and root development with higher nutrient levels, which create more and larger soil pores that decrease soil bulk density (Lister et al., 2004). A denser vegetative cover also affects soil physical properties due to litter production and root development (Guidi et al., 1985; Hiraoka and Onda, 2012). Since both SOC and SON can be mobilized in porous spaces within the soil matrix, a low bulk density of soil can store more SOC and SON. Our results agree with previous studies of soil carbon storage in various land, as Abera and Belachew (2011) found that carbon stores in forest soils were about twice the values in agriculture soils. Similarly, John et al. (2005) reported that forests had 52% more soil carbon content than grassland soils.

#### 4.2. Soil erosion by land-use type

Soil pedestal heights indicated that short-term soil erosion was greatest in the four land use types with the least understory biomass (Fig. 4). The correlation analysis showed that pedestal height was most strongly related to percent ground cover, as the four land uses with the highest pedestal heights did not have more than 63% ground cover (Tables 1, 2), while none of the land uses with more than 76% cover had any soil pedestals. Other studies also have shown soil erosion under a forest canopy with sparse understory vegetation and ground cover (Miyata et al., 2009). Taken together, these results indicate that both understory biomass and ground cover are important for reducing rainfall kinetic energy and rainsplash, but ground cover is more important. This result is supported by both modeling and field studies that show a strong, nonlinear relationship between percent surface cover and erosion (e.g., Larsen et al., 2009; Miller et al., 2011). The main difference between these other studies and our data set in Fig. 4b is that the threshold for no erosion is at least 76% ground cover. This relatively

high value can be attributed to the much higher amounts and intensities of rainfall in the study area during the summer monsoon rainy season.

The  $^{210}\text{Pb}_{\text{ex}}$  inventories for four of the forest types in our study and the shrubland ranged from 4280 to  $5678 \text{ Bq m}^{-2}$ , even though this was only measured in the top 5.35 cm. The very low value for *R. regia* can be attributed to the effect of terracing, while it is not clear why the  $^{210}\text{Pb}_{\text{ex}}$  value for *Acacia* spp. is so low as there was no evidence of soil pedestals. For comparison, the  $^{210}\text{Pb}_{\text{ex}}$  inventories for 0 to 30 cm at reference sites in Indonesia were nearly identical to most of our forest values at 4122 to  $5322 \text{ Bq m}^{-2}$ . Other comparisons also indicate that the  $^{210}\text{Pb}_{\text{ex}}$  inventories for four of our forest types and the shrub lands are generally within the range of reference conditions for a monsoon tropical climate (Huh and Su, 2004; Wakayama et al., 2010; Zhang et al., 2006). The lack of any detectable  $^{137}\text{Cs}$  in nine of the ten land use types suggests that this is due to very low levels of  $^{137}\text{Cs}$  fallout (Dercon et al., 2012; Uchida et al., 2009) rather than excessive erosion. Taken together, these results indicate that erosion rates for most of the forested areas on Luot Mountain have generally been low for much longer than the age of the current tree plantations and the replanted native forest.

The low  $^{210}\text{Pb}_{\text{ex}}$  contents in agricultural and bare lands were attributed to erosion by rainsplash and overland flow, and this is supported by the observed pedestal heights in the cassava and bare lands. Since silt-sized particles comprise 55–65% of the fine ( $<2 \text{ mm}$ ) fraction, the soil is highly susceptible to rainsplash and the resultant transport of small particles (Miller et al., 2011). Bare land is also susceptible to soil sealing, and the increase in rain splash and overland flow are key reasons why soil erosion rates generally are so much higher in agricultural lands than forests (Montgomery, 2007). No pedestals were observed in the lemon grass plots, but previous agricultural activities may be responsible for the current low inventory of  $^{210}\text{Pb}_{\text{ex}}$ . Because the spatial variability of soil erosion and radionuclide deposition can be high (Belyaev et al., 2009; Dercon et al., 2012), additional radionuclide data should be collected to confirm our initial results.

#### 4.3. Linkages of vegetation, macronutrients and soil erosion

Our findings suggest that the changes in land management and the associated changes in understory and ground cover can alter soil physical properties, macronutrient contents, and both short- and long-term soil erosion rates. The decrease in understory vegetation and ground cover is believed to be the primary cause of the increase in soil erosion and decrease in macronutrients (Table 4). Similarly, soil chemical richness is strongly linked to understory biomass litter biomass, and possibly the degradation of soil physical properties as exemplified by bulk density.

The linkages among vegetation, macronutrients and soil erosion also can be seen in component 2 which indicates vegetation condition and the short-term soil erosion in ten land-use types (Table 5). In general, each principal component in PCA is a group of linkable variables with similarity. In this component the effect of vegetation was quantified through the high positive loadings of understory biomass, litter biomass, and total ground cover, and soil pedestal height had an equivalent negative loading (Fig. 5). The relatively highest loadings were soil erosion indicator (soil pedestal height), and vegetation (known as understory biomass, litter and total ground cover), followed by soil nutrients such as total carbon and macronutrient (SOC and SON) in component 2, which indicates their tight linkage. Previous studies have shown that soil vegetation cover alters SOC and SON (Vanderschaaf et al., 2004). In flatter downslope areas deposition can enrich SOC and radionuclide inventories (Frye et al., 1982), but all of our plots were in sloping source areas. An upslope–downslope design focusing on a few land use types would be necessary to quantify both the loss and the redistribution of soils and macronutrients, and thereby apply the present results to larger scales.

## 5. Summary and conclusions

The objectives of this study were to: 1) compare vegetation cover, physical soil properties, macronutrient concentrations, and estimated short- and long-term soil erosion across ten different land uses in a hilly area of North Vietnam near Hanoi; and 2) evaluate the interrelationships among the various biological, chemical, and physical characteristics. Hence each land use was represented by three replicated plots in a relatively small study area to minimize the differences in soils, climate and other factors, and maximize the comparability among land uses, rather than trying to characterize the range of variability for each land use across a much larger area.

Soil organic carbon and nitrogen were strongly related to the amount of understory biomass than the amount of litter, although there was a strong correlation between the amount of litter and understory biomass. The amount of ground cover was a complex function as this was positively but not significantly correlated with both understory biomass and litter biomass, and inversely related to canopy openness. Soil organic carbon and nitrogen levels significantly declined with increasing bulk density, and this may be a reflection of both current and prior land use activities. Soil pedestal height was most closely related to the amount of surface cover, and surface cover also was the strongest explanatory variable for the amount of  $^{210}\text{Pb}_{\text{ex}}$ .

Forests did not necessarily have the highest amounts of litter or ground cover, or the lowest bulk densities. Hence they did not necessarily have the highest concentrations of soil organic carbon, nitrogen or phosphorus, or the lowest erosion rates. These results indicate that understory biomass, surface cover, and bulk density are the most important characteristics influencing soil nutrient status and erosion rates, and these three controlling factors are governed more by the specific characteristics of different types of forests or agricultural crops rather than the broad classification of land use (e.g., forest vs. agriculture).

The substantial differences in vegetation and soil physical properties among the specific land uses affect soil carbon and nutrient levels as well as erosion rates, indicating an important feedback loop between vegetation, soil conditions, and erosion rates. A simple characterization of forest or non-forest is not sufficient to calculate carbon and nutrient stocks, or to assess erosion risks. For these purposes, and for guiding land management in hilly areas such as North Vietnam, more specific information is needed on the local soils and vegetation characteristics.

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