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Comparative study of soil properties under various cultivation regimes of different crops

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Abstract. Establishment of cover crops is an effective way to reverse the soil fertility decline, which can be caused by a range of inappropriate traditional agriculture practices, particularly tillage and inorganic fertiliser application. In this study, soil properties were assessed under various cultivation regimes of different crops, including legumes, grass, and nursery natural rubber (NR) trees (*Hevea brasiliensis* Muell. Arg.), in southern Vietnam. The crops studied had all been growing for 7 years commencing in 1999, on light-textured Acrisols. Soils under the cultivation regime of creeping legumes including *Calopogonium caeruleum*, *Pueraria phaseoloides*, and *Stylosanthes gracilis* had significantly higher carbon (C) and nitrogen (N) concentrations and porosity than soils under the other management types studied. Soils under *Brachiaria ruziziensis* and *P. phaseoloides* had the highest aggregate stability. Cultivation regimes with tillage, field traffic, and inorganic fertilisers applied to nursery NR trees increased phosphorus (P) availability, but this was accompanied by increased soil compaction and reductions in most of the other soil properties analysed. Relative to the nursery NR cultivation, creeping-legume cultivation increased soil C concentration (by 95%), soil pH_{H2O} (by 19%), macro-aggregates (by 29%), and porosity (by 8%). From principal component analysis, three soil properties—soil organic carbon (SOC), porosity, and P availability—were selected as key indicators suitable for the evaluation of the effects of cultivation on soils. Establishment of *C. caeruleum* and *B. ruziziensis* was most effective in improving soil C content, and soil porosity was significantly higher under *C. caeruleum* and *P. phaseoloides*. These findings suggest that each cover crop had its own dominant agro-characteristics and that selection of a cover crop to either improve soil fertility or reduce compaction should be considered by farmers in this region.

Additional keywords: chemical properties, cover crops, legumes, rubber tree, soil.

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Introduction

Sizable areas of arable land all over the world have seen an alarming decline in soil productivity as a result of agricultural practices such as tillage and overuse of inorganic fertilisers. Declines in soil organic carbon (SOC), soil fertility (Solomon *et al*. 2007; Nguyen *et al*. 2008), and productivity (Kimetu *et al*. 2008) typically follow, and are accelerated by clearance and removal of natural forest trees and vegetation and subsequent agricultural management. Dechert *et al*. (2004) reported a typical example of soil fertility degradation influenced by agricultural cultivation where a progressive decrease in soil organic matter (SOM) occurred in soils under a maize crop while SOM increased under agro-forestry during the same period. Increasing global population and pressure for food security are likely to lead to further deforestation for agricultural development, with a consequent increase in the area of degraded soils worldwide.

Vietnam is a tropical and largely agriculture-based country, with as much as 70% of the national population dependent on agricultural activities (FAO 2008). The population of Vietnam is projected to increase by nearly 21.6% between 2010 and 2030 (United Nations 2008), and soil degradation is therefore regarded as a significant obstacle to achieving the required increase in food supply. Intensive use of soils for food production for an increasing national population has placed soil under an even more severe threat of degradation, decreased soil quality, and reduced productivity. The demand for food in Vietnam might therefore increasingly depend on a severely degraded soil resource; Thai (2000) reported that of ~10 Mha of degraded land in Vietnam on hilly, sloping areas, as much as 1 Mha is now entirely unsuited to food production.

In Vietnam, as with other similar tropical environments, the application of agricultural practices that conserve or improve soils is considered a key strategy for long-term sustainable agricultural development. An effective way to incorporate organic matter into soils and achieve soil amelioration is the use of plant residues and cover crops, and these are being promoted as a proven strategy for soil improvement and sustainability under long-term agricultural land use (FAO 2003). Kimetu *et al*. (2008) demonstrated that the addition of a range of organic matter sources had potential to reverse the decline in soil quality in tropical Kenya. However, different cover crops have their own attributes and ameliorating effects on soil properties. For example, Koutika *et al*. (2004) reported significant soil improvement under *Chromolaena odorata* and *Pueraria phaseoloides*, whereas other species (e.g. *Calliandra calothyrsus*) had an acidifying effect with an associated decrease in soil nutrient concentrations on the same soil.

The seven leguminous crops and two grasses tested in the current study are commonly planted to improve soil properties and to protect soil from erosion in Vietnam and in many other countries. The effects of these plants on soil properties are individually well documented elsewhere (Wilson *et al.* 1982; Fosu *et al.* 2003; Germani and Plenchette 2004; Koutika *et al.* 2004), but a comparison of these cover crops using data from disparate research programs may be inappropriate due to differences in environmental conditions of the various studies. There is, therefore, an urgent need to evaluate the effects of various commonly used cover crops in the climatic conditions of Vietnam in terms of soil physical and chemical properties.

In addition to cover crops, natural rubber (NR) tree (*Hevea brasiliensis* Muell. Arg.) is commonly planted in tropical regions for latex production. Currently, the global NR area is ~10 Mha, of which ~600 000 ha is established in Vietnam. Of this, an average of 18 000 ha of the crop has been replanted annually over the last 3 years. During its life cycle, the NR tree has a series of growing stages, from nursery to immature and mature periods. In the nursery stage, two types of the crop are normally produced, one to propagate high-yield rubber clones (budwood tree) and the other to produce seedlings, which are grafted with selected clone buds taken from the propagating nursery, yielding rubber stump, a common planting material.

The cultivation regime applied to produce the two types of nursery NR trees differs significantly from that of cover crop cultivation. Soil under the stump nursery is normally heavily ploughed annually at the start of every new stump season. Soil under the propagating garden is lightly tilled but severely impacted by intensive field traffic. In addition, rubber residues such as shoots, stem, and leaves from the budwood and stump nurseries are removed regularly through cultivation and soil preparation activities. Consequently, prolonging nursery cultivation regimes on the same sites without appropriate soil amelioration may induce a long-term decline in soil fertility. Whereas declining soil nutrient status in mature and immature rubber plantations is well documented with the length of time under cultivation (Karthikakuttyamma *et al.* 2000), similar data in NR nurseries have not been reported.

This study aimed to investigate and compare soil properties under different cultivation regimes of seven leguminous crops (including creeping and shrubby forms), two grasses, and two types of nursery NR tree. It was hypothesised that: (*i*) soil nutrient status would be significantly improved under creeping cover crop cultivation compared with shrubby forms, and (*ii*) cultivation regimes of nursery NR trees would lead to a degradation of soil physical properties in comparison with other cover crop cultivation regimes.

Materials and methods

Study site

The study was undertaken at the Natural Rubber Research Center of the Rubber Research Institute of Vietnam (RRIV). The Center is in Binh Duong province (11°33′N, 106°10′E), in the south-eastern region of Vietnam. The soil type at the site was dominated by a light-textured Acrisol (FAO/UNESCO), with clay content of 20–30% and sand content 50–60%. The site had been fallow and weeds controlled by mowing machine and occasionally by chemical treatment for a long period before establishment of cover crops and NR nurseries in June 1999. The study site is in the tropical zone and thus has high annual rainfall of ~1800–2500 mm and average temperature of 17−20°C. The altitude of the study site is 38 m above sea level.

Cover crops

The cover crops were established in 1999 from a research project funded by the Ministry of Agriculture and Rural Development, Vietnam, from 1996 to 2000. The project aimed to collect, maintain, and compare the most common cover crops currently available in Vietnam, with the aim of assessing their potential for soil improvement. The cover crops were maintained through 2007.

Leguminous crops

Seven leguminous cover crops, including *Calopogonium caeruleum*, *Pueraria phaseoloides*, *Stylosanthes gracilis*, *Chamaecrista rotundifolia*, *Crotalaria retusa*, *Tephrosia candida*, and *Flemingia congesta* were planted in 1999 in two plots each. The leguminous crops were morphologically separated into two groups, one of which, creeping legume, was characterised with creeping aboveground parts (*C. caeruleum*, *P. phaseoloides*, *S. gracilis*, *C. rotundifolia*). The other group comprised shrubby legumes with shrubby trunks (*C. retusa*, *T. candida*, *F. congesta*) (Table 1).

Grass

Two grasses, *Vetiveria zizanioides* L. (vetiver) and *Brachiaria ruziziensis*, were established in the same area. Major botanical characteristics of the grasses are shown as in Table 1.

Nursery NR trees

The NR trees at the nursery stage were established in adjacent sites (within 50 m), using the same establishment techniques as for cover crops. Two budwood and stump producing nurseries were set up and maintained to produce grafting and planting materials, respectively.

Budwood trees

The budwood nursery (propagating garden) was established to produce grafted buds of high-yield rubber clones. The budwood trees had been growing continuously in these plots, and shoots were cut and removed for grafting seasonally. At the end of every year, most shoots were cut and used for grafting, and the aboveground residues except for the main stock were removed for new shoot emergence.

Table 1. Information of the investigated crops and applied cultivation regimes

AGP, Aboveground part

No.	Crop	Botanical characteristics			Cultivation regime description
		Family	Nodulation	AGP	
		Regime 1: creeping legume			
1	*Calopogonium caeruleum*	Fabaceae	Yes	Creeping	Creeping legume + zero tillage + no field traffic + limited fertilisation[A]
2	*Pueraria phaseoloides*	Fabaceae	Yes	Creeping	
3	*Stylosanthes gracilis*	Fabaceae	Yes	Creeping	
4	*Chamaecrista rotundifolia*	Fabaceae	Yes	Creeping	
		Regime 2: grass			
5	*Vetiveria zizanioides*	Poaceae	No	Clump	Grass + zero tillage + no field traffic + limited fertilisation[A]
6	*Brachiaria ruziziensis*	Poaceae	No	Creeping	
		Regime 3: shrubby legume			
7	*Crotalaria retusa*	Fabaceae	Yes	Shrubby	Shrubby legume + zero tillage + no field traffic + limited fertilisation[A]
8	*Tephrosia candida* D.C.	Fabaceae	Yes	Shrubby	
9	*Flemingia congesta*	Fabaceae	Yes	Shrubby	
		Regime 4: nursery NR tree			
10	Nursery rubber stump	Euphorbiaceae	No	Woody	Nursery NR tree + tillage + field traffic + fertilisation
11	Propagating rubber	Euphorbiaceae	No	Woody	

[A] Full fertilisers were applied only at the establishment of the crops and N fertiliser for the first 2 years.

Rubber stump

The stump nursery was replanted annually to produce rubber stumps for each new planting season. Following a 10-month cycle in the nursery plots, the seedlings were grafted with grafting buds taken from the propagating garden, forming NR stumps, which were transplanted to the rubber plantations.

Experimental design

The 11 crops tested were categorised into four groups, three of which were grown with the same cultural practices (Table 1). Each cover crop was planted in two plots (replicates) of 20 m by 10 m (200 m^2). The budwood trees and NR stumps were planted in two large nurseries, of around 500 m^2 each, surrounding the cover crop plots. Each of the two nursery areas was divided into two subplots (two replicates) for measurements.

Cultivation regimes (treatments) as defined in the current study included type (group) of the tested crops and cultivation practices, including fertilisation, tillage, and field traffic. The first three cultivation regimes (Table 1) were applied to three groups of the cover crops, including creeping legumes, shrubby legumes, and grasses. The three regimes were similar in cultivation practices, but differed in crop types. Cultivation practices applied to the cover crops of the three regimes were minimal fertiliser application of 135 kg superphosphate and 67 kg KCl/ha at establishment only. For the first two years, the crops also had 250 kg urea/ha.year applied to encourage crop coverage, and no fertilisers were added in the following years. Weeding was done manually twice a year. Zero tillage and limited field traffic were applied to these regimes.

The fourth cultivation regime included nursery NR trees + full fertilisation + field traffic + tillage. The budwood plots received fertiliser applications of 500 kg urea, 687 kg superphosphate, and 286 kg KCl/ha for the first year, and 750 kg urea, 2062 kg superphosphate, and 287 kg KCl/ha for each of the following years. The stump plots received 960 kg urea, 960 kg superphosphate, and 400 kg KCl/ha.year. The nurseries were weeded using a mowing machine, causing field traffic in the nursery plots. Tillage was applied to the plots at every new establishment of a stump season to prepare the soil. The soil was also row-dug to 0.50 m depth for seedling growth. By the end of each year, most NR residues, including branches, leaves, and partial rubber roots, were removed for following seasons. The cultivation practices applied to the 11 tested crops were derived from common standard protocols in Vietnam.

Soil sampling and analyses

Chemical properties

Six years after the first establishment of the crops, soil samples were collected to assess physical and chemical properties. Soils were sampled in January, August, and December 2005 and in August and December 2006 (five measurements). For each plot, four subsamples were collected, each of which was sampled from eight to ten sites using an auger drilling to 0.1 m depth. It is commonly reported that soil properties, including SOM, total N, and bulk density, are influenced by land-use systems principally at the soil surface (e.g. Wilson *et al*. 1982); for this reason, soil samples were collected from the 0–0.1 m soil layer only. Each of the four subsamples was divided into two halves. The first four halves of four subsamples taken from the same plot were pooled into one composite sample, air-dried, ground, and sieved to <2 mm for the determination of total carbon (C), total nitrogen (N), available phosphorus (P), available potassium (K), and soil pH in water (pH_{H2O}). Total C was determined using the Walkley and Black method; total N was determined using a Kjeldahl digestion method; extractable P analysis was based on Murphy and Riley (1962), shaking 1 g of ground soil with 25 mL H_2SO_4 (0.05 M) for 5 min; available K was determined by shaking 1 g ground soil with 1 M ammonium acetate (pH 7) for 1 h, and AAS reading at 766.5 nm; pH_{H2O} was measured in 1 : 20 distilled water.

Aggregate stability

The other four halves of each plot's subsamples were individually used to quantify the proportion of aggregates in the various size classes, using a wet-sieving method (Cambardella and Elliott 1994; Six *et al.* 1998) with the following modifications. Soil samples were wet-sieved at field moisture content for aggregate separation to reduce any slaking effect from drying and rapid rewetting. Four sieves were stacked in the order 2000 μm, 1000 μm, 500 μm, 250 μm. The sieve stack was shaken in distilled water vertically at an amplitude of 3 cm at 25 cycles per minute. Materials remaining on individual sieves were collected by washing carefully with distilled water, dried at 50°C in an oven for 24 h, and weighed.

Physical properties

Soil samples for measurement of bulk density, particle density, and porosity were taken using a 100-cm^3 corer. The soil samples from each plot were taken at the same time as those for chemical and aggregate sampling. Samples for physical analysis were weighed and oven-dried at 105°C for 48 h until a constant weight was reached for bulk density determination. Soil particle density was determined using pycnometer method (Hao *et al.* 2006). Soil porosity was calculated from bulk density and particle density of the same sample.

Statistical analyses

The study followed a completely randomised design. The number of replicates varied from four (for nursery NR tree and grass) to six (shrubby legume) and to eight (creeping legume). The number of replicates was reduced to two when the measured data were analysed to test any differences among the 11 crops.

Data from the five measurements made between January 2005 and December 2006 were averaged for statistical analysis. Analysis Of variance (ANOVA) was conducted and Student's *t*-test at $P = 0.05$ used to stratify the means. The ANOVA procedure was applied following Ott and Longnecker (2001, p. 855), based on a completely randomised, single-factor design with varying replicates, after verifying homogeneity and normal distribution. All data processing was done using JMP 7 software (SAS Institute Cary, NC, USA) and Microsoft Excel. The ANOVA model was: $y_{it} = \mu + \beta_i + \varepsilon_{it}$, where y_{it} is the observation from plot t applied with treatment i, μ is overall mean, β_i is effect due to treatment i, and ε_{it} is random error.

To reduce the number of soil variables and then select the best representative variables for soil assessment, principal component analysis (PCA) was performed, based on a correlation matrix. Eight soil parameters—total C, total N, available P, available K, pH_{H2O}, macro-aggregate (size >250 μm), bulk density, and porosity—were integrated with PCA, forming eight principal components (PC). As suggested by Jolliffe (1986) and Khattree and Naik (2000) and used by Skrbic and Durisic-Mladenovic (2007), only PCs having eigenvalues ≥ 1 were retained for further consideration. Within each PC, only eigenvectors having absolute loading values (coefficient) >90% of the maximal absolute coefficient were retained for analysis (Andrews and Carroll 2001).

Following PCA analysis, soil variables were further reduced to a final set using procedures applied by Andrews and Carroll (2001). Briefly, selection of variables within each PC was made on the basis of weighting, based on (*i*) multivariate correlation coefficients, which showed strength of the relationships of the selected variables; and (*ii*) practicality (i.e. the role of the variable, interpretability).

Results

Soils under creeping legumes had the highest soil C and N contents, while soils under NR trees in nurseries with fertiliser application had significantly lower C and N concentrations. The creeping legumes, including *C. caeruleum*, *P. phaseoloides*, *S. gracilis*, and *C. rotundifolia*, had higher soil C concentration (+95%), soil N concentration (+105%), and soil pH_{H2O} (+19%) than the NR trees. Available P in cultivated soils under NR trees was ~3.5 times higher than under the other management regimes. Soil pH_{H2O} was significantly higher under creeping legumes and grasses and lowest under shrubby legumes and nursery NR trees (Fig. 1).

The proportion of soil macro-aggregates (>250 μm) was similar in the three regimes of cover crops, varying from 74 to 78%. The lowest proportion of macro-aggregates (64%) was observed under nursery NR trees (Fig. 2). Soils under cover crops had better soil physical properties with higher porosity and lower bulk density than nursery NR cultivation (Fig. 3). Macro-aggregates and porosity of soil under creeping legumes were higher by 29% (aggregate proportion) and 8% (porosity) than under nursery NR trees.

Organic C concentrations in soils under *C. caeruleum*, *S. gracilis*, and *B. ruziziensis* were significantly higher than under the other crops tested (Fig. 4). The lowest C concentrations were observed in soils under nursery NR trees. Similarly, pH_{H2O} was lowest in soil planted with the NR stump and budwood trees and *T. candida* (Fig. 4).

Compared with other crops, soils under *B. ruziziensis*, *P. phaseoloides*, and *C. rotundifolia* had the largest proportion of water-stable soil aggregates (Fig. 4). More than 80% of soil particles under these crops formed macro-aggregates. The soil from the NR nurseries had the lowest proportion of water-stable macro- aggregates. Porosity was highest in soils under *C. caeruleum* (47%) and *P. phaseoloides* (46%) and was lowest in the nursery NR cultivated soil (42%).

Of the eight soil properties analysed in the current study, soil C concentration was highly and positively correlated with total N concentration, pH_{H2O}, macro-aggregate, and porosity (Table 2), but negatively correlated with available P and bulk density. The quantity of macro-aggregates was also significantly and positively correlated with soil C, soil N, pH_{H2O}, and porosity but negatively correlated with available P and bulk density.

Three PCs, having eigenvalues >1, were retained and shown in Table 3. These PCs cumulatively represented 82%

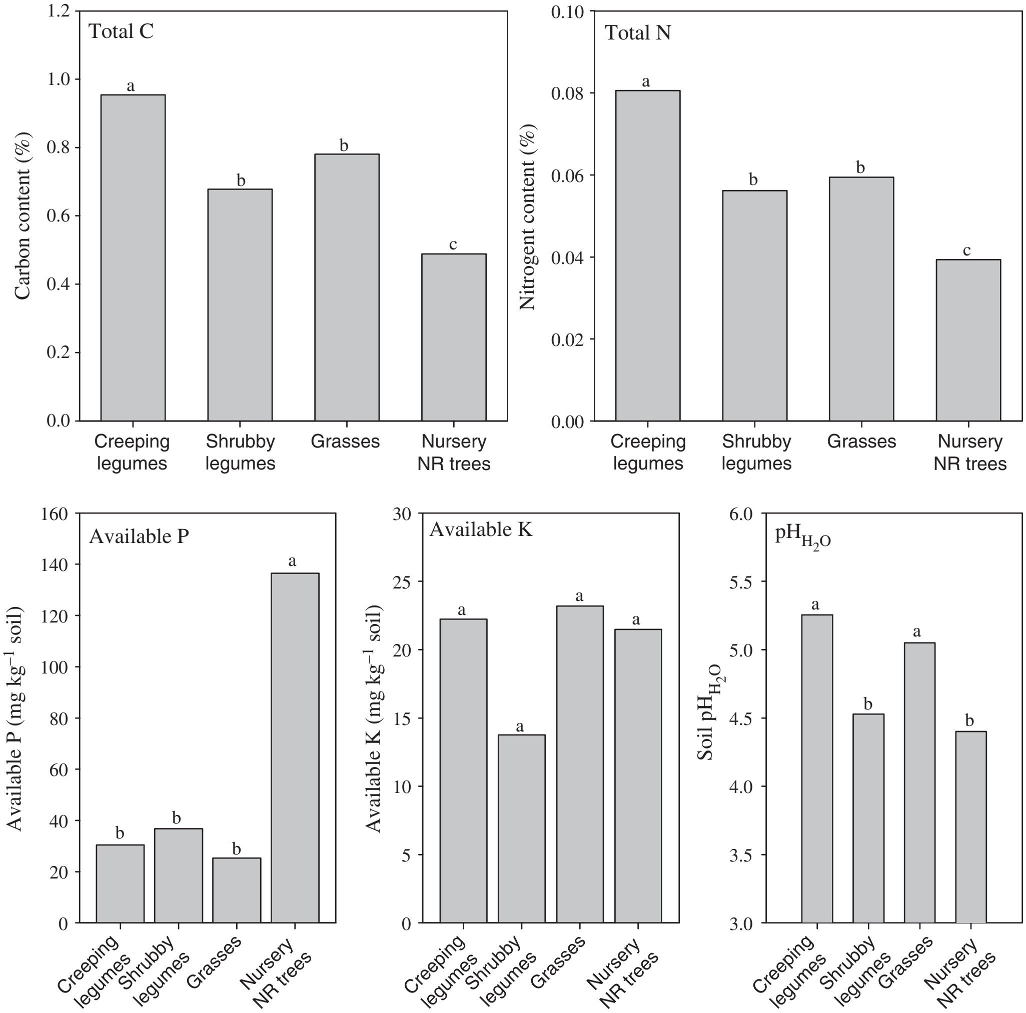

Fig. 1. Effects of cultivation regimes on soil chemical properties. Bars with the same letter are not significantly different at $P = 0.01$.

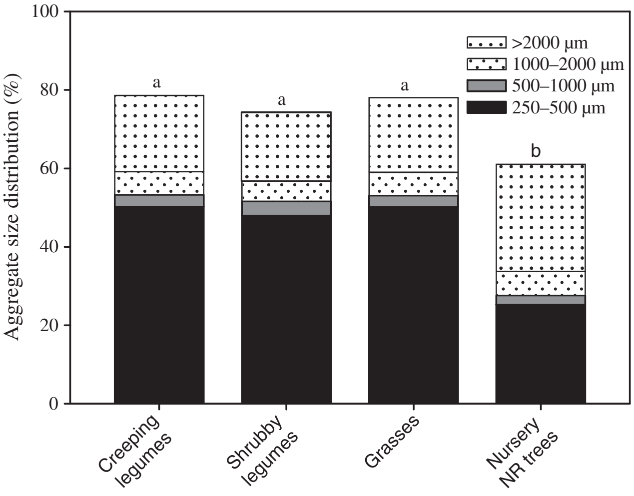

Fig. 2. Soil macro-aggregates (>250 µm) influenced by different cultivation regimes. Bars with the same letter are not significantly different at $P = 0.05$.

of total variation. Eigenvectors having absolute loading value >90% of the maximum were retained such that, within each PC, two eigenvectors, total C and total N for PC1, available P and available K for PC2, and bulk density and porosity for PC3, with highest absolute loading values, were selected for further consideration. Because the two selected variables within each PC were highly correlated with each other, just one of these was selected to use as a criterion to evaluate the impacts of cultivation regime and crops. Total C, available P, and porosity were selected to represent the appropriate minimum dataset (Fig. 5).

Discussion

Based on the botanical traits (Table 1), the 11 crops tested were separated into four groups: (*i*) creeping legume (*C. caeruleum*, *P. phaseoloides*, *S. gracilis*, *C. rotundifolia*), (*ii*) shrubby legume (*C. retusa*, *T. candida*, *and F. congesta*), (*iii*) grass (*V. zizanioides*, *B. ruziziensis*), and (*iv*) nursery NR tree (NR budwood tree and NR stump). The legumes of the first two groups had common characteristics of N fixation through

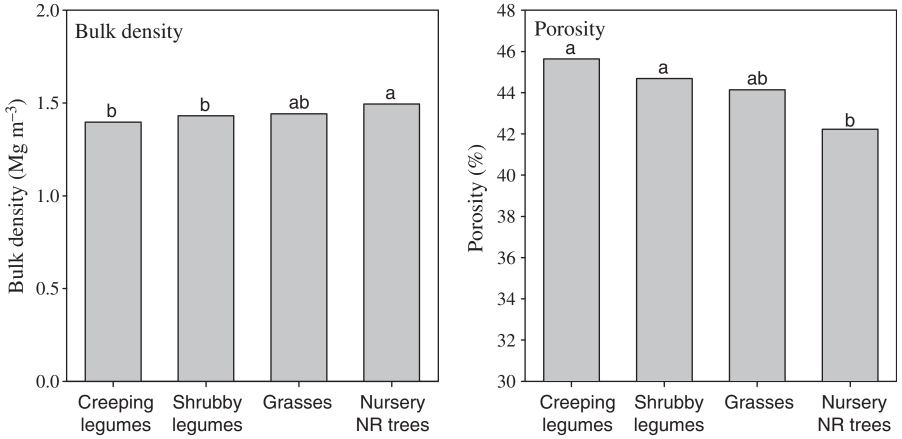

Fig. 3. Bulk density and porosity of soil under different cultivation regimes. Bars with the same letter are not significantly different at $P = 0.01$.

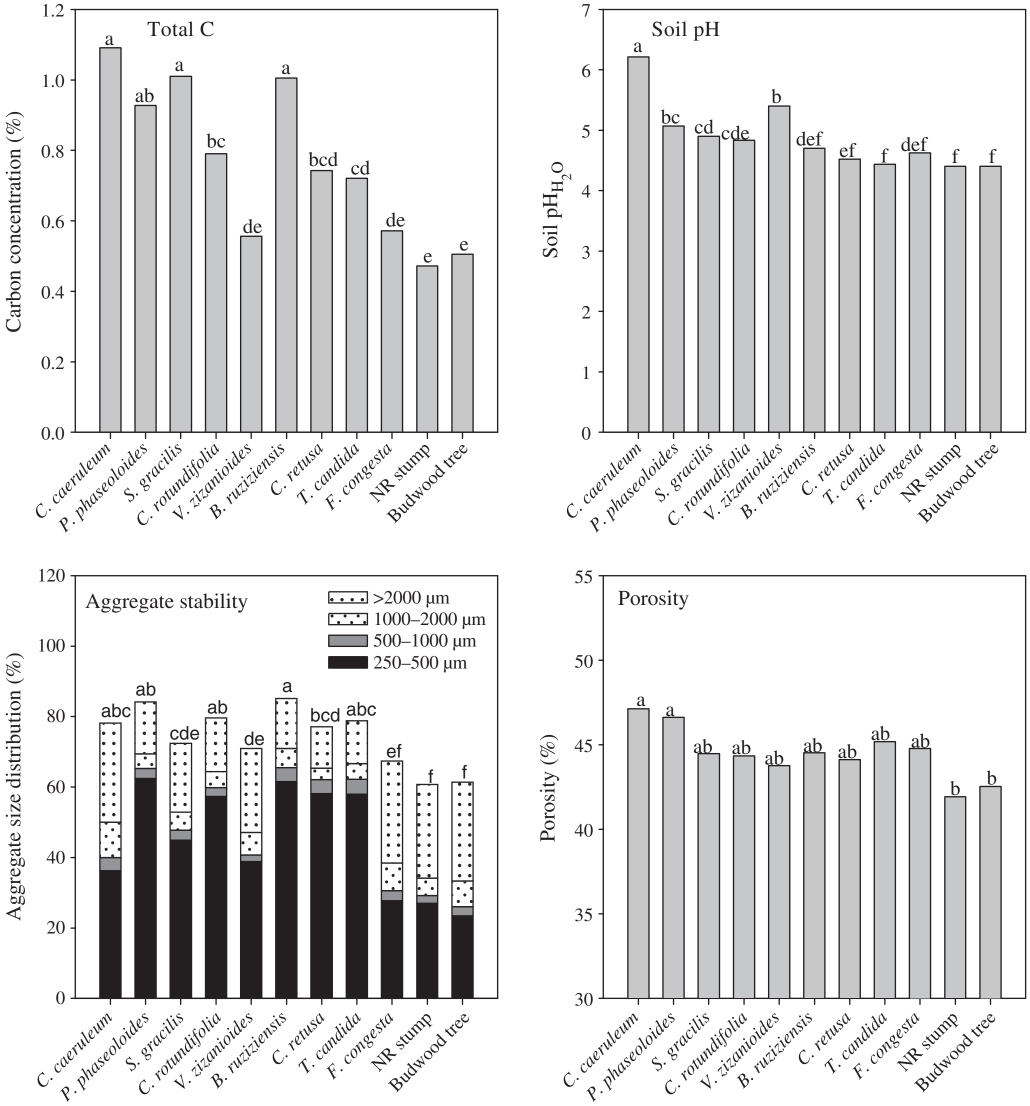

Fig. 4. Selected chemical properties (total carbon, pH, aggregate distribution, and porosity) of soils under different tested crops. Bars with the same letters indicate no significant difference between treatments at $P = 0.05$.

Table 2. Correlation coefficients, *r*, of the analysed soil properties

*$P < 0.05$; n.s., not significant ($P > 0.05$). Number of observations = 55

Parameter	Total C	Total N	Avail. P	Avail. K	pH_{H2O}	Macro-aggregates	Bulk density
Total N	0.95*						
Available P	–0.38*	–0.38*					
Available K	0.21n.s.	0.21n.s.	0.33*				
pH_{H2O}	0.50*	0.57*	–0.16 n.s.	0.27*			
Macro-aggregate	0.62*	0.56*	–0.64*	–0.16 n.s.	0.28*		
Bulk density	–0.44*	–0.44*	0.16 n.s.	0.05 n.s.	–0.44*	–0.42*	
Porosity	0.35*	0.35*	–0.11 n.s.	–0.02 n.s.	0.30*	0.38*	–0.92*

Table 3. Results of principal component analysis

Bold values are those having absolute values >90% of the maximal absolute value in each PC

Index	PC1	PC2	PC3
Eigenvalue	3.73	1.55	1.31
Percentage	46.66	19.39	16.40
Cumulative percentage	46.66	66.05	82.45
	Eigenvectors		
Total C	**0.45**	0.10	0.30
Total N	**0.45**	0.16	0.27
Available P	–0.26	**0.54**	–0.29
Available K	0.04	**0.58**	0.21
pH_{H2O}	0.33	0.31	0.08
Macro-aggregate >250 µm	0.39	–0.35	0.15
Bulk density	–0.39	–0.04	**0.55**
Porosity	0.35	0.03	**–0.61**

nodulation, but were different in aboveground growth form (creeping or shrubby forms). The former, especially *C. caeruleum* and *P. phaseoloides*, were observed to provide better soil surface cover (around 90%) after 4–6 months of establishment than the shrubby leguminous crops in the study.

Vetiveria zizanioides and *B. ruziziensis* are commonly recommended in Vietnam and other tropical countries as cover crops or as a hedge or barrier, protecting soil from erosion and degradation (Pansak *et al.* 2008). The former has a deep root system, which has been reported to reach depths of as much as 3 m (Mickovski 2007), with a high clumpy shape, while the latter is characterised by a shallower root system and a creeping aboveground habit. Pansak *et al.* (2008) reported that hedgerow establishment using *B. ruziziensis* resulted in more intense leaching of N in the soil but a smaller ratio of N loss from runoff than that with *V. zizanioides*. This suggests that *V. zizanioides* may be more appropriate for mitigating nutrient leaching, whereas *B. ruziziensis* may be better in slowing surface runoff of nutrients. In our study, we found higher N concentration and higher pH under creeping legumes, suggesting more efficient N supply and retention but also limited N leaching. However, with special characteristics such as great adaptability to different soil conditions and large biomass (Antiochia *et al.* 2007), *V. zizanioides* has been widely planted for soil erosion control and for detoxifying soil heavy metal contamination (Chen *et al.* 2000; Antiochia *et al.* 2007).

The budwood trees were planted in 1999 and maintained until 2006, with limited tillage applied to the plots, while the NR stumps were replanted annually and the soil under the stumps was heavily ploughed upon initiating every new stump season. The two types of the rubber trees in nurseries shared a common natural rubber cultivar, but differed in maintenance and life cycle. They were commercially planted to produce planting materials for new NR establishment and, thus, were very different from the other crops tested, which were usually used as soil protectors.

Results from the current study strongly support our hypothesis that cultivation of creeping legumes was more effective at enhancing soil nutrient contents than was cultivation of shrubby legumes. The effects of cover crops have been documented to be a consequence of surface protection, root system, biomass, and faunal activities (Obi 1999). During our experiment, we observed (visually, not direct measurement) that the creeping legumes had a greater leaf biomass and a better soil surface cover than the shrubby varieties. A likely consequence was that creeping legumes returned a considerable amount of plant litter to soil, resulting in higher C and N concentrations and ultimately better soil physical and chemical condition, as shown in Figs 1, 2, and 3. In contrast, the shrubby legumes showed lower concentrations of C and N and lesser soil physical and chemical condition, probably due to smaller annual biomass return and lower soil surface cover.

In contract to the effects of cover crops, intense agricultural cultivation apparently led to a significant reduction of soil fertility (FAO 2003). Higher soil C and N concentrations were consistently found under cover crops compared with nursery NR trees (Fig. 1), and at our sites, cover crops seem to have enhanced soil condition in contrast to cultivation. This result conforms to work elsewhere. For example, Wilson *et al.* (1982) reported an increase (average 43%) in soil C and N contents after a 2-year establishment of legumes (*P. phaseoloides*, *Stylosanthes guianensis*, *Stizolobium deeringianum*, *Psophocarpus palustris*, *and Centrosema pubescens*) and grasses (*B. ruziziensis*, *Paspalum notatum*, *and Cynodon nlemfuensis*) from a 5-year cultivated soil. Obi (1999) similarly reported an increase in soil nutrient contents by both leguminous crops and grasses, compared with the initial nutrient status.

The various crops we examined had different morphological and physiological characteristics and influenced soil properties in different ways. For example, *V. zizanioides*, with a more prolific root system (Mickovski *et al.* 2005), resulted in better soil physical properties, with higher porosity and aggregate stability, compared with the nursery NR trees (Fig. 4). We

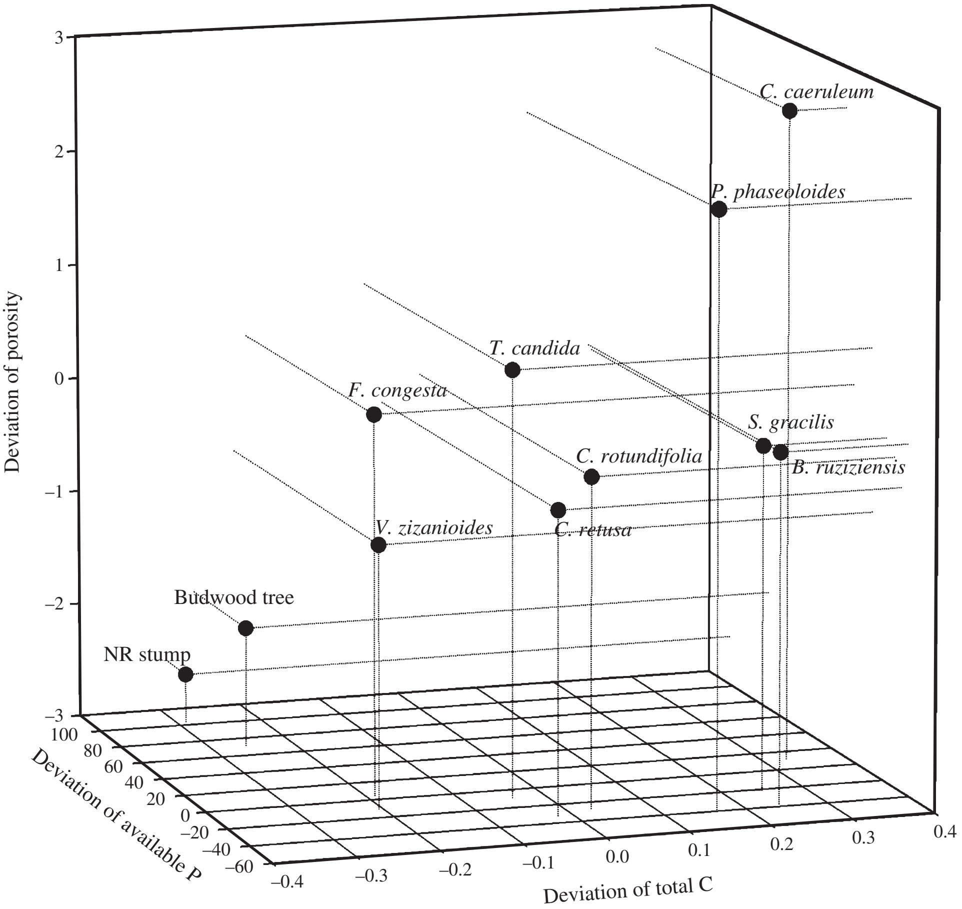

Fig. 5. Distribution of the 11 crops on a three-dimensional plot made from three selected soil variables, determined through principal component analysis.

also compared soil N concentrations between leguminous crops and grasses and found that, as might be expected, soil N concentrations were, on average, higher under the legumes. This is probably due to N fixation by leguminous crops via symbiotic relationship between legumes roots and rhizobia (Viera-vargas *et al.* 1995; Sanginga *et al.* 1996; Gil *et al.* 1997). The N fixation might occur more strongly with creeping legumes than with shrubby legumes, reflected through averaged total N greater in soil planted with creeping legumes (0.081% N) than in soil planted with shrubby legumes (0.056% N). Likewise, Sanginga *et al.* (1996) reported higher N fixation by *Stylosanthes* and *P. phaseolodes* than *Crotoraria* in an 8-week pot experiment and showed that N fixation varied among the crops tested in their study and depended on biomass production.

Soil planted with NR trees in nurseries had lower in C, N, and pH than soil cultivated with other crops in the current study. Tillage, as applied to the NR tree nurseries, may be the major reason accounting for these observations. Tillage practices have been documented to accelerate soil degradation through declining SOM content, aggregate stability, and soil biodiversity (Lal 1993). For example, SOM is typically found to be lower under more intense cultivation systems (Beare *et al.* 1994; Oorts *et al.* 2006) and is usually increased where annual or perennial vegetation cover is established (Nguyen and Marschner 2005). In addition, annual removal of biomass of NR trees, including grafted-budding wood from the budwood nursery and planting materials from the stump plots, may be another reason for a lower C concentration in the NR soil than soil under other tested crops. Heavy field traffic resulting from intensive activities, such as chemical fertiliser addition, weeding, pruning, grafting, and budwood-cutting, may also cause soil compaction (Fig. 3), leading to lower soil porosity of nursery NR trees (Fig. 3).

Cropping with NR trees in nurseries resulted in higher soil P availability (Fig. 1) compared with the other crops studied. The higher P availability in the soil under nursery NR trees was presumably due to annual P fertiliser addition, which was applied more sparingly to the cover crops. Continuous application of inorganic fertilisers probably also accounts for a lower pH_{H2O} in soil planted with nursery NR trees (Figs 1 and 3) relative to soil cultivated with the other crops. Acidification of the soil by inorganic fertilisation is well documented (e.g. Sumner and Noble 2003). Xu *et al.* (2002) explained an observed pH decrease as a result of nitrification of the added fertiliser-N, followed by NO_3^- leaching. These mechanisms were probably operating in the light-textured Acrisols that we studied, which facilitate nitrification and NO_3^- leaching, especially under the more intense cultivation regimes. In addition, high annual rainfall coupled with low SOM in the current study site may significantly contribute to nutrient leaching. Xu *et al*. (2002) also noted that soil acidification was accelerated through removal of alkaline plant residues from fields, and the removal of rubber tree biomass from the NR plots probably also contributed to the soil acidification that we observed.

A significant correlation also existed between C content and other soil properties, such as total N, available P, pH_{H2O}, macro-aggregates, bulk density, and porosity (Table 2), suggesting an important role of SOM in moderating a range of soil properties (Brady and Weil 2002). Soil organic C, for example, contributes to nutrient storage potential of N, P, and sulfur while binding soil particles, forming soil structure and stable aggregates A particularly strong correlation ($r = 0.95$) was found between soil C and N concentrations (Table 2), indicating that a major portion of soil N was bound to SOM.

Compared with nursery NR trees, lower soil P availability under cover crops was likely a consequence of limited fertiliser application during the 7-year period of cultivation. Additionally, the legumes may need more P for nodulation, and therefore have a greater P demand (Sadowsky 2005). In some P-limited cases, legumes might even develop additional mechanisms, such as root exudation of organic acids (Dakora and Phillips 2002; Singh and Pandey 2003) or acidification of the rhizosphere (Hinsinger and Gilkes 1997), to acquire more soil P for their demands, and thus further lower soil P availability.

Although part of total soil P is well known to exist in the organic form (Brady and Weil 2002), we found a significant, negative correlation between soil C content and extractable P (Table 2). This, however, can be largely explained by the management and fertiliser regime at our sites. For example, (*1*) the cultivation regime of nursery NR trees reduced the relative soil C concentration while soil P was increased by annual P addition, and (*2*) cultivation of other cover crops enhanced soil C concentration compared with cultivation systems but did not receive equivalent P inputs.

Our results suggest that soil porosity and aggregate stability improved under cover legume crops (Table 2) and in agriculture; these are two of the most important physical properties of the soil. Porosity and aggregate stability have been widely reported to increase as a result of organic matter amendment (García-Orenes *et al.* 2005), and Arvidsson (1998) related the magnitude of soil porosity or air content directly with SOM content. Similarly, we found a significant correlation between SOM content and macro-aggregate proportion (Table 2), indicating that SOM played an important role in enhanced soil aggregation stability. Annual tillage of the NR stump plot in the current study appears to have resulted in a reduction in soil macro-aggregates and SOM content, compared with the other crops (Figs 1 and 2). Cambardella and Elliott (1993) concluded that the degradation of soil macro-aggregate structures and subsequent reduction of SOM were caused by intense cultivation. They also suggested that there was a linkage between loss of soil aggregate stability and loss of soil organic C derived from the particulate organic matter fraction. The proportion of soil macro-aggregates has been linked directly to the addition and presence of plant debris, plant roots, and fungal hyphae in the soil (Tisdall and Oades 1982; Jastrow *et al.* 1998) and therefore reflects SOM status and biological health. In the current study, plant roots and fungal hyphae-forming mycorrhizae may play a significant role in stabilising soil structure and forming macro-aggregates, as indicated through a much greater correlation coefficient between SOC and macro-aggregates ($r = 0.62$) than that between SOC and porosity ($r = 0.35$). In fact, most of the tested crops, rubber tree and *P. phaseoloides* (Jayaratne *et al*. 1986; Ikram *et al.* 1994), *C. caeruleum* (Ikram *et al.* 1993), *S. gracilis* (Yao *et al.* 2005), *C. retusa* (Germani and Plenchette 2004), *B. ruziziensis* (Sansamma and Pillai 1998), and *V. zizanioides* (vertiver grass) (Wong *et al.* 2007) were able to form a mutually beneficial association with mycorrhizae. Such external mycorrhizal fungi have been shown to have a significant, positive impact on soil aggregate stability after only one growing season (Bearden and Petersen 2000; Denef *et al.* 2001). The formation and colonisation of mycorrhizae from the studied crops may both increase soil aggregate stability and enhance crop growth due to greater nutrient acquisition by the association.

Other factors such as clay content and iron oxides have also been reported to significantly contribute to soil aggregation (Kodešová *et al.* 2009). However, in our study, the contribution of clay and iron oxides may be less important because the studied soil was a coarse Acrisol with clay content of 20–30%. We therefore conclude that improved porosity and aggregate stability reflect improved soil condition under cover crops.

Based on PC analyses, three soil properties—extractable P, SOC, and porosity—were selected and used as a minimum dataset to evaluate the effects of cultivation regimes on soil properties (Fig. 5). The highest P availability in soil under nursery NR trees was due to annual P addition. The P fertiliser is stable in soil and soil P accumulates in the agricultural, cultivated soil over time. The other two soil variables, soil SOC and porosity, were considered important because they were directly influenced by the cultivation regimes and were two of the most important properties reflecting the magnitude of soil degradation (Tian 1998). The three soil properties selected as a minimum dataset from this study are similar to those selected by Wilson *et al.* (2008) (bulk density, pH, C, P, and sodium) in New South Wales, Australia. Sodium, however, is not important in the soil from this study (a light-textured Acrisol). Additionally, pH was found to be well correlated with C from this study and, thus, could be eliminated in the presence of soil C. We therefore conclude that the three key soil parameters—C, P, and porosity—represent a good indicative minimum dataset in assessing soil fertility under influence of cover crops and agricultural crops in Vietnam.

Creeping legumes, especially *C. caeruleum* and *P. phaseoloides*, were most beneficial to soil properties in the current study. Cultivation regime with nursery natural rubber tree was clearly shown to deplete soil fertility, relative to other regimes, and thus needs an appropriate soil care program to mitigate these negative impacts. In addition, *B. ruziziensis* and *S. gracilis* seem to have the greatest potential in this environment for improving soil C content, and more research is required under different farming circumstances (e.g. sloping and marginal soils) to test the suitability of these management approaches for sustainable agricultural development in the region.

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