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Does *Tephrosia candida* as fallow species, hedgerow or mulch improve nutrient cycling and prevent nutrient losses by erosion on slopes in northern Viet Nam?

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Abstract

Agroforestry is considered to be a promising alternative to short-fallow shifting cultivation or other monocropping systems. An on-farm experiment was established in 1996 in northern Viet Nam to examine the contribution of the leguminous bush *Tephrosia candida* (Roxb.) D.C. as a fallow or hedgerow species and as a mulch producer to improve nutrient cycling and prevent nutrient losses by erosion. The systems tested were upland rice monocropping (Mono), natural fallow (NaFa), fallow of *Tephrosia* (TepFa), hedgerow intercropping with upland rice (*Oryza sativa* L.) and internal mulching using pruned *Tephrosia* biomass (TepAl), and upland rice with external mulching using *Tephrosia* biomass (TepMu). Over two cropping seasons, from April 1996 to April 1998, nutrients recycled and inputs and exports were recorded, as well as changes in C-, N- and P-pools, and in pH in the 0–5 cm topsoil layer.

The *Tephrosia* systems (TepFa, TepAl, TepMu) prevented nutrient losses by erosion effectively. Compared to the NaFa system, the TepFa system accumulated 34% more N in the above-ground plant parts and increased topsoil N by 20%, probably due to N-fixation. There was a trend that the less labile P-pools (NaOH-P) were reallocated into the more labile P-pools (Bicarb-P) in the soil of the TepFa system. Burning released significant amounts of the inorganic P-pools in both the NaFa and TepFa systems and this effect seemed to be more pronounced in the TepFa than in the NaFa. Organic input to crop export ratios for N and P were >1 in the TepAl and TepMu treatments. This was due to a sufficient quantity and quality of the *Tephrosia* mulching material. However, moderately labile NaOH-extractable organic P seemed to be depleted in the topsoil due to high P uptake in the TepMu treatment. Thus, nutrient cycling and nutrient balances were improved under the *Tephrosia* systems. But for long-term P sustainability, there is a belief that a combined use of mulching and mineral P fertiliser is needed.

Keywords: Slash and burn; Erosion; Nutrient cycling; Improved fallow; Viet Nam

1. Introduction

Shifting cultivation (ShC) occupies about 3.5 million ha in the highlands of Viet Nam (Do Dinh, 1994).

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Short-fallow ShC system is the common ShC practice and can be described as burning the vegetation cover, followed by cropping of upland rice (*Oryza sativa* L.) or maize (*Zea mays* L.) during the cropping phase, followed by 2 or 5 years of natural fallow period. Short-fallow ShC on steep slopes (>25°) with acid soil and high rainfall is not considered to be a sustainable land use system, due to high nutrient losses mainly through erosion. There tends to be a decline in crop yields and an increasing land degradation (Hoang Fagerström, 2000).

Through improved management by combining hedgerow intercropping and planted fallow, it should be possible to increase crop yields in ShC systems and at the same time decrease the adverse environmental impacts of these systems (Fagerström, 1998). Planted fallows, i.e. cultivation of selected species during the fallow phase of a ShC system (Nair, 1993; Snapp et al., 1998) aim at an optimisation of the nutrient cycling in order to minimise the need for external inputs and to maximise their efficiency (Sanchez, 1994). The advantages of hedgerows as erosion barriers and as producers of fuel-wood, mulch (in situ mulch) and animal fodder have been reported (Nair, 1993; Kang, 1997). Planting of leguminous trees with deep root systems to enhance the nutrient uptake from deeper soil layers, combined with N inputs from N fixation, is considered to be one of the most effective ways of improving nutrient cycling on-farm in South Africa (Snapp et al., 1998). Many agroforestry systems accumulate P in their biomass and return it to the soil when the litter decomposes. Through cycling, some less available inorganic forms of P in the soil may be converted into potentially available organic forms (Sanchez and Palm, 1996). Litter fall and root mass were recommended by Schroth et al. (1995) to be criteria for fallow tree efficiency in terms of soil fertility and crop yield. However, leguminous plant materials provide high quality organic inputs, which can meet crop demands for N but which are unlikely to satisfy crop demand for P (Palm, 1995; Palm et al., 1997).

In many upland soils of the tropics, P rather than N provides the main limitation to plant growth (Gijsman et al., 1996). Soil P occurs in inorganic and organic forms with different rates of P release (*ortho*-phosphate formation). Deficiency of plant-available P is common in highly weathered, acid soils in the tropics, due to adsorption to Al and Fe oxides. Erosion and P export through harvest products deplete the P storage in the soil. Studies in the steep lands of Rwanda showed that about half of the negative N and P balance is due to run-off and erosion losses (Smaling, 1993). Gains of plant-available P are connected with litter from stumps and roots, ashes from burnings and with P released by mineral weathering. The P storage in any soil vastly exceeds the current demand for plant uptake, but most of this P occurs in forms not immediately accessible to roots or mycorrhiza.

It is important to understand the soil P dynamics in order to optimise P cycling. Exchange between stable and more labile P-pools is of great importance for long-term P availability. P-pools with decreasing chemical solubility may imply a decrease in plant availability (Buresh et al., 1997), although this relationship is not wholly straightforward (Magid et al., 1996). Soil P-fractions could be obtained through sequential fractionation. The fractionation steps include anion exchange resin, sodium bicarbonate ($NaHCO_3$), sodium hydroxide (NaOH), hydrochloric acid (HCl) and $H_2SO_4 + H_2O_2$ extractions (Hedley et al., 1982). Inorganic bicarbonate-extractable P (Bicarb-Pi) and organic bicarbonate-extractable P (Bicarb-Po) are considered to be labile P-pools, while inorganic NaOH-extractable P (NaOH-Pi) and organic NaOH-extractable P (NaOH-Po) are less labile but potentially available P-pools (Buresh et al., 1997). Tiessen et al. (1984) showed that the Bicarb-Po and NaOH-Po may play a significant role in providing available P in more weathered soils, with low inputs of inorganic fertiliser P.

Tephrosia candida (Roxb.) D.C. (Leguminosae family, Papilionoideae sub-family) is native to the tropical foothills of the Himalayas in India and is cultivated and naturalised throughout South–East Asia (Oyen, 1997). The species is a promising for agroforestry in the Tropics and was chosen in the present study due to its high biomass yield, dense vegetative cover, deep root system and its nitrogen fixation ability (Nguyen Tu and Thai, 1993; Kadiata et al., 1996; Gichuru, 1991).

The effects of *Tephrosia* as a fallow species, hedgerow species or mulch producer in the upland rice-based system, in terms of net returns and farmer's response, were presented in Hoang Fagerström et al. (2001). This paper presents the effects of the *Tephrosia* systems in terms of erosion control and nutrient cycling, including soil P availability. Ratios between nutrient inputs (including soil nutrients recycled through fallow biomass, and crop residues as well as external inputs), and nutrient exports (van Noordwijk, 1999) as well as exchanges between P-pools of different lability were used to evaluate nutrient effects of the systems tested. The *Tephrosia* systems were compared to the existing fallow crop rotation system and the existing continuous monocropping system.

2. Materials and methods

2.1. General description of the study site and design of the experiment

A field experiment was established in 1996 on a hill with an average slope of 22–24°, close to the Rong Can village in Hoa Binh province (21°N, 105°E, elevation 100 m above sea level), approximately 45 km SW of Hanoi. The area consists of high hill ranges intersected by narrow valleys, where paddy fields are common. The climate is characterised by monsoons, with a dry period from October to March and moderate to high rainfall from April to September. The mean annual rainfall was 1772 mm in 1986–1996, 1664 mm in 1996, 1441 mm in 1997 and 968 mm in 1998. The mean air temperature throughout the year was 22.8 °C in 1986–1996. Gneiss (ancient metamorphic rocks), sandstone of Paleozoic origin and limestone of Permian age are the dominant geological formations in the region (Young, 1985).

The soil is silty clay to clay, reddish brown and moderately acidic, and classified as a Haplic Ferralsol (FAO, 1990). The field experiment had a randomised block design with three blocks. For 2 years before the installation of the experiment in 1996, both maize (*Zea mays* L.) and upland rice (*Oryza sativa* L.) occupied the area of blocks 1 and 2, while the area of block 3 was under natural fallow. No fertilisers were used for these crops. The experimental treatments and the management operations during 1996–1998 are given in Table 1. The treatments Mono and NaFa represented the cropping and fallow period of the existing short-fallow ShC. The “improved” practices were represented by the treatments TepFa, TepAl, and TepMu. NaFa and TepFa were representatives of the fallow period of ShC systems, while Mono, TepAl and TepMu were representatives of the continuous

Table 1
Experimental treatments and management operations during 1996–1998 at the experimental site in Hoa Binh province, Viet Nam[a]

Abbreviation	1996				1997				1998
	April	May	June–August	October	April	May	June–August	October	April
Mono	Upland rice monocropping								
	C & B	RS		H	C & B	RS		H	C & B
NaFa	Natural fallow								
	C & B	Re-growth natural vegetation			Re-growth natural vegetation				S & B
TepFa	*Tephrosia* fallow								
	C & B TcS	*Tephrosia* growth			*Tephrosia* growth				S & B
TepAl	Upland rice with hedgerows[b] and mulching[c]								
	C & B TcS	RS	Pr & M	H	C & B	RS, Pr & M	Pr & M	H	C & B
TepMu	Upland rice with mulching[d]								
	C & B	RS	M	H	C & B	RS, M	M	H	C & B

[a] C & B: cleaning the field and burning; TcS: *Tephrosia* sowing; RS: rice sowing; Pr & M: pruning *Tephrosia* hedgerows and mulching; H: harvest; S & B: slash and burn.
[b] Hedgerows of 150 cm width, consisting of three rows of *Tephrosia*.
[c] Mulching of biomass of *Tephrosia*, pruned from the hedgerows in the same plot.
[d] Mulch of pruned biomass of *Tephrosia* transferred from outside of the plot.

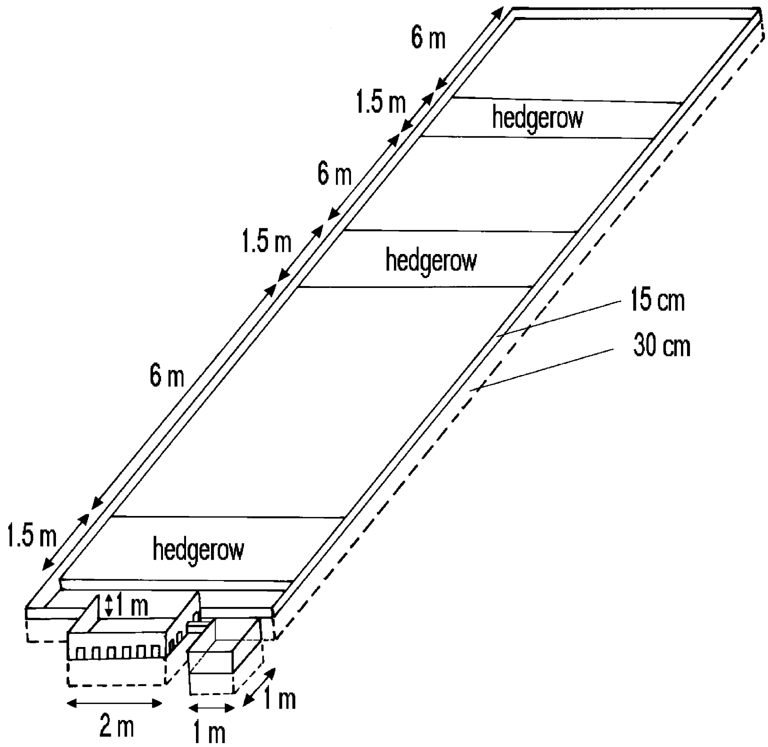

Fig. 1. Design of the experimental plots (the hedgerows were designed only for the plots of TepAl treatment).

cropping systems. The design of the experimental plots is shown in Fig. 1.

2.2. Treatment management and plant sampling

After installation of the plots in 1996, *Tephrosia* seeds (local variety named "Cot khi") were sown in 50 cm rows manually in the TepFa treatment and in hedgerows of the TepAl treatment along the contour lines. The plots of the NaFa treatment were left for the re-growth of natural vegetation. Slash and burn in the NaFa and TepFa treatments was carried out in April 1998. The vegetation was clear cut, weighed in the field, divided into fuel-wood (diameter $>$ 0.8 cm) and remaining parts (leaves and stems with a diameter $<$ 0.8 cm) left in the field. The parts left in the field were air-dried and burned four weeks later. Samples were collected randomly to determine the dry weights of the removed parts and of those left in the field (oven-drying at 60 °C for about 60 h of 300 g sub-samples) and later used for chemical analyses.

Pruning and mulching was carried out as follows: The biomass of *Tephrosia* pruned from a nearby hedgerow treatment was transferred to the TepMu treatment. These hedgerows represented approximately 20% of additional area used for the TepMu treatment. The biomass of *Tephrosia* pruned in the hedgerows of the TepAl treatment was mulched in the same plots. Crop yields were expressed on a total area basis (including the area under hedgerows). The pruned biomass was weighed, chopped into pieces of about 2 cm length and mulched. Samples were collected in the field, weighed and put in paper bags which were brought to the laboratory on the same day for dry weight determination, and later used for chemical analyses.

Upland rice planting, weeding, application of pesticide and harvesting were carried out according to local practice (Hoang Fagerström, 2000). Harvesting was carried out on the entire plots. Tillers with grains and straw of about 30 cm length were cut and weighed before they were removed from the field. Dry matter content was measured separately for grains and straw on oven-dried samples of 200 g. The samples were collected randomly during the harvest and dried at 55 °C for about 60 h and later used for chemical analyses. Litter was collected in the fallow treatments, NaFa and TepFa, prior to slash-and-burn of the fallow biomass in April 1998, using a frame of 1 m^2. All litter accumulated on the ground within the frame at three positions per plot—“upper”, “middle” and “lower” slope—was collected, weighed and later re-calculated on a hectare basis. The crop residues left in the field were estimated directly after harvest, using the same procedure as for the litter estimation.

The biomass of the hedgerows was estimated in April 1998 using a non-destructive method. The stem diameter was measured at 25 cm height from the ground of all plants along a 2 m line on the right-hand side of each hedgerow (looking in the upslope direction). Three measured plants, which represented the maximum, median and minimum stem diameters, were collected per plot to be used as samples for estimating the correlation between stem diameter and plant dry matter. For the three plant samples, the plant dry matter was measured separately for woody and leafy parts after oven-drying at 55 °C for about 60 h. The regression equations of the woody and leafy parts were

$$\text{Stems (g)} = -46.2 + 123\,\text{D (cm)};\ n = 9;\ P < 0.001;\ R^2 = 89.6\%;\ D > 0.4\,\text{cm} \quad (1)$$

$$\text{Leaves (g)} = -19.9 + 52.5\,\text{D (cm)};\ n = 9;\ P < 0.05;\ R^2 = 45\% \quad (2)$$

The low correlation level between stem diameter and dry matter of leaves ($R^2 = 45\%$) could be explained by the pruning practice, which led to changes in the branching pattern of *Tephrosia* in the hedgerows. The total dry matter of all plants was then estimated for the whole row of 5 m, recalculated on a kg DM ha^{-1} basis.

2.3. Erosion measurements

Soil loss through erosion and surface run-off from each plot was determined during an entire erosion cycle, from the end of April to the beginning of October in 1996 and 1997. The experimental plots were especially designed for these purposes (Fig. 1). A detailed description of the plots and the tanks for collecting sediment is given in Hoang Fagerström (2000).

The amount of soil eroded was determined after each individual rain storm whenever sedimented soil material was observed in the tanks situated at the lower part of the plots. Sediment material was collected for chemical analyses twice each year (end of June and middle of August) and surface run-off water in August 1996 and August 1998 only. Sediment samples were collected by carefully mixing the sediment in the bottom of the big tank, taking three sub-samples of 145 ml at different spots and then pooling them. The bulked sample was divided into two parts. One part was oven-dried at 105 °C for determination of dry matter. The other part was air-dried, crushed, sieved through a 2 mm sieve and later used for chemical analyses. Sampling of run-off water (including suspended sediments) was carried out at three depths in the tanks: 20, 40 and 60 cm above the bottom. Three bottles were attached with rubber bands to a stick at the above-mentioned depths. A representative sample of approximately 200 ml was then collected from the three bottles. The water samples were shaken and filtered through a wetted millipore filter paper (0.45 μm) for 24 h. The particles collected on the filter were oven-dried at 105 °C in order to determine the amount of sediment in the water suspension. The filtered water was preserved with 4 M H_2SO_4 and kept in 100 ml plastic bottles for chemical analyses.

2.4. Soil sampling

Soil sampling was carried out in April 1996 (during the field experiment installation) in the Mono treatment and in all treatments in April 1998 (before the slash-and-burn). Bulked samples consisting of 16 sub-samples per plot at a soil depth of 0–5 cm were collected with an auger. Sampling for dry bulk density was performed in May 1997 (for Mono, TepMu, TepFa and NaFa) and in May 1998 (for TepAl), using metal cylinders with a diameter of 5 cm, at the same depth as for the soil sampling, and at three positions in all plots: “upper”, “middle” and “lower” slope. The bulk density values were used for converting soil nutrient concentrations to a kg ha^{-1} basis. Bulk density was not measured in 1996 to minimise plot disturbance.

The effects of burning were studied using soil samples collected directly before and after burning. For burned sub-plots ($1\,m^2$ per plot), 4–5 samples at the soil depth of 0–5 cm were collected with an auger and mixed to obtain one composite sample. The reason for using the burned sub-plots instead of the whole plot was that on the sampling days, the weather and the slashing vegetation were not suitable for burning in the entire plots. The samples collected were air-dried, ground and sieved through a 2 mm-sieve for chemical analyses.

2.5. Chemical analyses

Soil texture was determined by the hydrometer method (van Reeuwijk, 1993), total C and total N with a Leco CNS Analyzer; soil pH in a 1:2.5 soil–water suspension (Anonymous, 1994a), exchangeable base cations (Na, K, Ca, Mg) by extracting the soil with 1 M CH_3COONH_4 at pH 7 solution (van Reeuwijk, 1993). CEC by saturating the soil with 1 M Na-acetate solution, then extracting the soil with 0.25 M $BaCl_2$ (Anonymous, 1994b), run-off water was analysed colorimetrically for total N (flow injection) and total P (Swedish Standard, 1984 SS 028127, 1984). The plant samples were analysed for C, N and P. Total C and N were determined by the same method as for the soil analyses. Total P was determined after HNO_3 digestion of plant tissue for analysis by inductively-coupled plasma (ICP) emission spectroscopy (Chao-Yong and Schulte, 1985). Soil and sediment samples of the Mono treatment collected in 1996 were analysed for P-fractions and total P, while soil samples of all treatments collected in 1998 were analysed for bicarbonate-extractable P (Bicarb-P) and NaOH-extractable P (NaOH-P) fractions only. These two fractions were chosen for this study due to their importance for P availability (Tiessen et al., 1984). A modified version of the Hedley et al. (1982) sequential procedure was used, where some of the extraction steps, such as the anion exchange resin (Resin-Pi) and sonicated NaOH-P (for samples of 1996 and 1998), HCl-P, and residue P (for samples of 1998) were excluded. All analyses were in duplicate. All fractions were analysed for P by using a colorimetric ascorbic molybdate method (Watanabe and Olsen, 1965).

2.6. Statistical analyses

Treatment effects were statistically evaluated by the following four orthogonal contrasts, using Genstat 5 Release 3.2 (The parameters 1.5 and 0.5 were introduced to facilitate comparisons between treatment combinations which contained different numbers of individual treatments)

$$\text{Fallow versus crop} = 1.5 \times (\text{NaFa} + \text{TepFa}) - (\text{Mono} + \text{TepAl} + \text{TepMu}) \quad (3)$$

$$\text{NaFa versus TepFa} = \text{NaFa} - \text{TepFa} \quad (4)$$

$$\text{TepAl and TepMu versus Mono} = 0.5 \times (\text{TepAl} + \text{TepMu}) - \text{Mono} \quad (5)$$

$$\text{TepAl versus TepMu} = \text{TepAl} - \text{TepMu} \quad (6)$$

Burning effects, i.e. comparisons of soil nutrient status before and directly after burning in the fallow treatments (TepFa and NaFa), were evaluated by the same statistical method as above. Statistical significance was set at $P < 0.1$ due to the fact that some of the results gave P-values very close to 0.05.

F-tests using GLM in the MINITAB statistical computer package were used to evaluate the differences, in C-, N-, P-pools and pH, between the soil in 1996 and in 1998 of the Mono treatment. Linear regressions were calculated using the MINITAB statistical computer package for the regression between stem diameter and dry matter in the hedgerows, and for a regression on changes in the NaOH-Po pool versus P uptake in rice grains.

3. Results

3.1. Erosion and nutrient cycling

Over two cropping seasons, from April 1996 to April 1998, up to $76\,Mg\,ha^{-1}$ soil was eroded, and soil loss was roughly five times lower in the fallow treatments (NaFa and TepFa) than in the cropping treatments (Mono, TepAl, TepMu) (Table 2). These findings were estimated per hectare total area, including cropped area (TepMu 1, Mono, TepAl) and the area

Table 2
Erosion and nutrient losses through erosion during 1996–1997 at the field experimental site in Hoa Binh province, Viet Nam (P concentrations in run-off water were below the detection limit)

Losses	Treatments					ANOVA[a]			
	Mono (A)	NaFa (B)	TepFa (C)	TepAl (D)	TepMu (E)	Fallow versus crop	B versus C	D & E versus A	D versus E
Soil loss (Mg DM ha^{-1})									
1996 (1664 mm)[b]	55	23	2	36	57	***	N.S.[c]	N.S.	N.S.
1997 (1441 mm)	21	0	0	1	9	**	N.S.	***	N.S.
Sum	76	23	2	37	66	***	N.S.	N.S.	N.S.
N (kg ha^{-1})									
1996	98	44	5	75	117	***	N.S.	N.S.	N.S.
1997	46	0	0	1	16	**	N.S.	***	N.S.
Sum	144	44	5	76	133	***	N.S.	N.S.	N.S.
P (kg ha^{-1})									
1996	37	13	1.5	22	32	***	N.S.	N.S.	N.S.
1997	13	0.0	0.0	0.4	5	**	N.S.	***	N.S.
Sum	50	13	1.5	22	37	***	N.S.	*	N.S.
Surface run-off water (m^3 ha^{-1})									
1996	1342	736	473	1065	1359	***	N.S.	N.S.	N.S.
1997	1942	379	261	351	1240	**	N.S.	**	*
Sum	3284	1115	734	1416	2599	***	N.S.	**	*
N (kg ha^{-1})									
1996	3.1	1.7	1.1	2.4	3.1	***	N.S.	N.S.	N.S.
1997[d]	2.4	0.5	0.4	0.8	2.8	***	N.S.	N.S.	**
Sum	5.5	2.2	1.5	3.2	5.9	***	N.S.	N.S.	**
Sum (soil loss + soil run-off)									
N losses (kg ha^{-1})	150	46	6.5	79	139	***	N.S.	N.S.	N.S.
P losses (kg ha^{-1})	50	13	1.5	22	37	***	N.S.	*	N.S.

[a] See Section 2.6.
[b] Rainfall of the current year (mm per year).
[c] N.S.: non-significant.
[d] N concentration of the surface run-off water of 1997 was estimated as a mean of 1996 and 1998.
* $P < 0.1$.
** $P < 0.05$.
*** $P < 0.01$.

under hedgerows (TepAl). The amount of soil loss decreased in the order Mono (100%) > TepMu (87%) > TepAl (49%) > NaFa (30%) > TepFa (3%).

There were 79–185 kg ha^{-1} N and 6.6–10.5 kg ha^{-1} P accumulated in the above-ground biomass and litter. The nutrients accumulated mainly in the fallow biomass in the NaFa and TepFa treatments, in mulching material in the TepAl treatment and in the removed crop in the Mono and TepMu treatments. TepFa had 34% larger N accumulation than NaFa, while TepAl had 110% larger N accumulation and 59% larger P accumulation compared to Mono (Table 3). However, not all the N gained in the *Tephrosia* fallow compared to the natural fallow returned to the soil, but part of it (35 kg N ha^{-1}) was exported from the field in the form of fuel wood. Therefore, there was no significant difference in organic N cycled to the soil between the two fallow systems (Table 4).

At least 24–150 kg ha^{-1} N and 1.7–7.8 kg ha^{-1} P were returned to the soil (root biomass was not measured), while 42–207 kg ha^{-1} N and 2.5–55 kg ha^{-1} P

Table 3
Nutrient accumulation in above-ground biomass and litter of the treatments, tested during April 1996–April 1998 at the experimental site in Hoa Binh province, Viet Nam

Parameters	Treatments					ANOVA[a]			
	Mono (A)	NaFa (B)	TepFa (C)	TepAl (D)	TepMu (E)	Fallow versus crop	B versus C	D & C versus A	D versus E
N ($kg\,ha^{-1}$)									
Fallow biomass[b]		117	99				N.S.[c]		
Litter[d]		18	51				**		
Mulching[e]				100					
Crop residue[f]	24			23	12			**	***
Crop removal[g]	57			33	65			N.S.	**
Standing biomass[h]				14					
Fuel-wood[i]		3	35				**		
Total	81	138	185	170	79	***	**	***	***
P ($kg\,ha^{-1}$)									
Fallow biomass		6.8	4.0				N.S.		
Litter		1.0	2.1				*		
Mulching				5.2					
Crop residue	1.7			1.5	0.7			***	***
Crop removal	4.9			3.3	6.3			N.S.	**
Standing biomass				0.5					
Fuel-wood		0.1	1.0				**	**	
Total	6.6	7.9	7.1	10.5	7	N.S.	N.S.	**	*

[a] See Section 2.6.
[c] N.S.: non-significant.
[b] Including stems (diameter < 0.8 cm) and leaves left in the field prior to burning in April 1998.
[d] Accumulated surface litter at the end of the fallow period in April 1998. The N- and P-contents of the litter were estimated using the N- and P-contents of the fallow biomass left in the field in the same treatment.
[e] *Tephrosia* biomass for mulching was pruned from the hedgerows within the treatment.
[f] Crop residues were estimated for the harvest in October 1997 using data from the harvest in October 1998.
[g] Grain and straw yield removed from field. The yield of the TepAl treatment was calculated per unit area including hedgerows.
[h] Standing biomass measured in April 1998. The N- and P-content of the hedgerow biomass were estimated using the N- and P-content of the fallow biomass of the TepFa treatment.
[i] Fuel-wood was collected when slashing and burning the fallow biomass in April 1998.
* $P < 0.1$.
** $P < 0.05$.
*** $P < 0.01$.

were exported from the systems (Table 4). The export of N and P was mainly through erosion (15–94% of total N export and 60–99% of total P export). The ratio between organic inputs (recycled plus external inputs) and totally eroded N and P ranged from 0.2 to 23 and from 0.03 to 4, respectively (Table 4). This ratio for N was greater than 1 in NaFa, TepFa and TepAl, close to 1 (0.9) in TepMu, whereas the ratio for P was greater than 1 only in TepFa. The ratios between organic inputs (recycled plus external inputs) and total biomass removals of N and P of the cropping systems (Mono, TepAl and TepMu) were 0.4–3.7 and 0.3–2, respectively, while for the fallow systems they were 4.3–45 and 6–78, respectively. All fallow and cropping systems, except the Mono system, had a ratio between organic inputs (recycled plus external input) and total biomass removal of N and P which was ≥1 (Table 4).

The content of N and P in the organic input materials ranged from 6.6–34 $g\,kg^{-1}$ for N and 426–1917 $mg\,kg^{-1}$ for P (Table 5). The *Tephrosia* mulching material had the largest ($P < 0.01$) content

Table 4
Nutrients recycled, external input and export of the treatments tested during April 1996–April 1998 at the experimental site in Hoa Binh province, Viet Nam

Parameters	Treatments					ANOVA[a]			
	Mono (A)	NaFa (B)	TepFa (C)	TepAl (D)	TepMu (E)	Fallow versus crop	B versus C	D & E versus A	D versus E
N (kg ha^{-1})									
Organic N input[b]	24	135	150	123	130	***	N.S.[c]	***	N.S.
Total N export	207	49	42	112	204	***	N.S.	N.S.	N.S.
Eroded N[d]	150 (72)[e]	46 (94)	6.5 (15)	79 (71)	139 (68)	***	N.S.	N.S.	N.S.
Removed N[f]	57 (28)	3 (6)	35 (84)	33 (29)	65 (32)	**	**	N.S.	**
P (kg ha^{-1})									
Organic P input[b]	1.7	7.8	6.1	6.7	6.8	**	N.S.	***	N.S.
Total P export	55	13	2.5	25	43	***	N.S.	*	N.S.
Eroded P[d]	50 (91)[g]	13 (99)	1.5 (60)	22 (87)	37 (85)	***	N.S.	*	N.S.
Removed P[f]	4.9 (9)	0.1 (1)	1.0 (40)	3.3 (13)	6.3 (15)	**	**	N.S.	**
Input: eroded									
N	0.16	2.9	23	1.6	0.9	***	***	N.S.	N.S.
P	0.03	0.6	4	0.3	0.2	**	**	N.S.	N.S.
Input: removed									
N	0.4	45	4.3	3.7	2	***	**	***	*
P	0.3	78	6	2	1	**	**	*	*

[a] See Section 2.6.
[b] Organic N and P inputs, include organic N and P recycled, and were calculated for each treatments as follows: Mono, crop residues; NaFa and TepFa, fallow biomass + litter; TepAl and TepMu, crop residue + mulching, where the mulch of TepAl was pruned from the hedgerows within the treatment, but the mulch of TepMu was transferred from outside the plots.
[c] N.S.: non-significant.
[d] Eroded N and P: N and P in soil mass + N in surface run-off water (see Table 2).
[e] Values in brackets are percentage of total N export.
[f] Removed N and P: N and P removed from the field in crop harvest (Mono, TepAl, TepMu) and in fuel-wood (NaFa and TepFa; see Table 3).
[g] Values in brackets are percentage of total P export.
* $P < 0.1$.
** $P < 0.05$.
*** $P < 0.01$.

Table 5
N- and P-contents of the organic input materials used in the treatments during April 1996–April 1998 at the experimental site in Hoa Binh province, Viet Nam

Content	Organic input materials				ANOVA[a]			
	NaFa[b] (A)	TepFa[c] (B)	Mulch[d] (C)	Crop residue[e] (D)	A & B versus C	A & B versus D	A versus B	C versus D
N (g kg^{-1})	11.8	15.6	34	6.6	***	***	***	***
P (mg kg^{-1})	681	629	1917	426	***	***	N.S.[f]	***

[a] Four contrasts were tested: A & B versus C = 0.5 × (NaFa + TepFa) − mulch; A & B versus D = 0.5 × (NaFa + TepFa) − crop residues; A versus B = NaFa − TepFa C versus D = mulch − crop residues.
[b] Slashed biomass of the natural fallow left in the field prior to burning.
[c] Slashed biomass of the *Tephrosia* fallow, including stems (diameter < 0.8 cm) and leaves left in the field prior to burning.
[d] Mulch was *Tephrosia* biomass pruned from *Tephrosia* hedgerows.
[e] Crop residues was upland rice straw left in the field after harvest.
[f] N.S.: non significant.
*** $P < 0.01$.

of both N and P, compared to the fallow biomass and the crop residues. Fallow biomass of the TepFa treatment had 32% larger N-content ($P < 0.01$) than the NaFa treatment.

3.2. Soil nutrient changes

The concentrations of C-, N-, and P-fractions and pH in the sediments collected during the rainy season of 1996 were very similar to those in the 0–5 cm soil layer (Hoang Fagerström, 2000) (Table 6). After the two experimental years (April 1996 and April 1998), no significant changes in pH, total C, total N, Bicarb-Po, Bicarb-Pt, NaOH-Po and the sum of Bicarb-P and NaOH-P were found in the 0–5 cm soil layer of the Mono treatment. However, Bicarb-Pi, NaOH-Pi, NaOH-Pt and the C/N ratio were significantly reduced (Table 6).

Soil N increased by 20% in TepFa in comparison to NaFa. TepAl and TepMu increased by 20 and 10%, respectively, in comparison to Mono. The labile to moderately labile organic P (Bicarb-Po plus NaOH-Po) seemed to increase (20 kg) in the fallow treatments (TepFa and NaFa), compared to the start of the experiment, while in the continuous cropping systems (Mono, TepAl, TepMu) this P-fraction decreased slightly. In TeFa and NaFa, Bicarb-Pt increased by 360% of and NaOH-Po decreased by 16%, compared to the continuous cropping systems (Mono, TepAl, TepMu). In TepFa, the NaOH-Po was 29% less ($P < 0.01$) than in NaFa. Similarly, NaOH-Po was 24% less ($P < 0.01$) in TepMu compared TepAl (Table 6). Assuming that the soil P in the Mono treatment in 1996 was representative of the whole experimental site, the calculated decline in the NaOH-Po pool between April 1996 and 1998 in the 0–5 cm soil layer was significantly correlated ($P < 0.05$) with grain P accumulated in the continuous cropping systems (Mono, TepAl and TepMu; Fig. 2).

Burning increased ($P < 0.01$), the pH by 1.4 units in the 0–5 cm soil layer of the fallow systems (NaFa and TepFa; Table 7). Similarly, both Bicarb-Pi and

Table 6
C-, N-, and P-fractions and pH in the 0–5 cm soil layer of the treatments in April 1996 and April 1998 prior to burning at the experimental site in Hoa Binh province, Viet Nam

Parameter	Treatments						ANOVA[a]				
	1996	1998					A & B	Fallow C versus crop	C versus D	E & G versus A	E versus G
	Mono (A)	Mono (B)	NaFa (C)	TepFa (D)	TepAl (E)	TepMu					
pH-H_2O	5.0	4.9	5.3	4.9	5.0	5.0	N.S.[b]	N.S.	*	N.S.	N.S.
C/N	10.5	9.7	10.4	9.9	9.5	9.4	*	***	**	N.S.	N.S.
C (mg ha^{-1})	11	10	11	11	12	10	N.S.	N.S.	N.S.	N.S.	N.S.
N (mg ha^{-1})	1	1.0	0.9	1.1	1.2	1.1	N.S.	*	**	**	*
P-fractions (kg ha^{-1})											
Bicarb-Pi	2.7	1.0	4.0	2.8	1.7	2.0	**	***	N.S.	N.S.	N.S.
Bicarb-Po	11	22	50	71	14	12	N.S.	**	N.S.	N.S.	N.S.
Bicarb-Pt	14	23	55	74	16	14	N.S.	***	N.S.	N.S.	N.S.
NaOH-Pi	39	29	27	30	29	28	***	N.S.	N.S.	N.S.	N.S.
NaOH-Po	92	76	73	52	84	64	N.S.	***	***	N.S.	***
NaOH-Pt	130	105	100	82	113	92	*	***	***	N.S.	***
Bicarb-P + NaOH-P (kg ha^{-1})											
Pi	41.7	30	31	33	31	30	***	N.S.	N.S.	N.S.	N.S.
Po	103	98	123	123	98	76	N.S.	***	N.S.	N.S.	N.S.
Pt	145	128	154	156	129	106	N.S.	***	N.S.	N.S.	N.S.

[a] See Section 2.6.
[b] N.S.: non-significant.
* $P < 0.1$.
** $P < 0.05$.
*** $P < 0.01$.

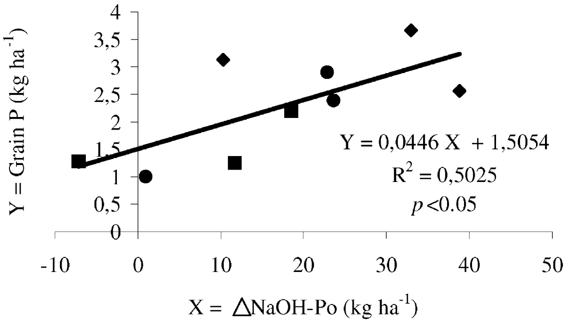

Fig. 2. Relationship between ΔNaOH-Po (change in NaOH-Po between April 1996 and April 1998) in the 0–5 cm soil layer and P-content of upland rice grain in October 1997 (squares, Mono; dots, TepAl; diamond, TepMu).

NaOH-Pi were significantly increased after burning. Furthermore, Bicarb-Pi increased by 27% more ($P < 0.05$) in TepFa than in NaFa. Bicarb-Po was significantly reduced in both fallow systems.

4. Discussion

4.1. Soil erosion

Soil loss rates for the two wet seasons 1996 and 1997 (up to 76 mg ha^{-1}) were at the low end of the range in comparison with other findings in the area. According to Thai Phien and Tu Siem (1996), annual crops such as upland rice and cassava (*Manihot esculenta* Crantz) in monoculture caused soil losses ranging from 70–100 Mg ha^{-1} year^{-1}. The somewhat low results in the present study could be due to low rainfall at the site (1664 mm in 1996 and 1441 mm in 1997) in comparison with the average rainfall 1984–1998, which was 1783 mm, as well as the low rain intensity (Thai Phien, personal communication). The lowest yearly rainfall during this 15-year-period was 1434 mm in 1995 (data from a nearby meteorological station). The similarity of the nutrient contents in the sediment and in the 0–5 cm soil layer indicated

Table 7
Burning effects on C-, N-, and P-fractions and pH of the 0–5 cm soil layer of the treatments in April 1998 at the experimental site in Hoa Binh province, Viet Nam

Parameters	Treatments						ANOVA[a]			
	NaFa bb[b] (A)	NaFa ab[c] (B)	NaFa (ab−bb) (C)	TepFa bb (D)	TepFa ab (E)	TepFa (ab−bb) (G)	A versus (B)	D versus (E)	(A + D) versus (B + E)	(B−A) versus (E−D)
pH	5.7	7.1	1.4	5.9	7.1	1.2	***	***	***	N.S.
C/N	11.0	11.2	0	10.5	10.4	0	N.S.[d]	N.S.	N.S.	N.S.
C (T ha^{-1})	14	14	0	13	16	3	N.S.	N.S.	N.S.	N.S.
N (T ha^{-1})	1.2	1.2	0	1.2	1.5	0.3	N.S.	N.S.	N.S.	*
P-fractions (kg ha^{-1})										
Bicarb-Pi	4 (2)[e]	15 (9)	11(7)	4 (2)	18 (10)	14 (8)	***	***	***	**
Bicarb-Po	63 (29)	55 (31)	−8 (2)	76 (38)	39 (22)	−37 (16)	N.S.	*	**	N.S.
Bicarb-Pt	67 (31)	70 (40)	3 (8)	80 (40)	57 (32)	−23 (−7)	N.S.	N.S.	N.S.	N.S.
NaOH-Pi	31 (15)	49 (28)	18 (13)	29 (14)	54 (31)	25 (16)	**	**	***	N.S.
NaOH-Po	116 (54)	58 (33)	−59 (−21)	94 (46)	66 (37)	−27 (−9)	N.S.	N.S.	N.S.	N.S.
NaOH-Pt	148 (69)	107 (60)	−41 (−8)	123 (60)	120 (68)	−2 (7)	N.S.	N.S.	N.S.	N.S.
Bicarb-P + NaOH-P (kg ha^{-1})										
Pi	36	64	28	33	72	39	***	***	***	N.S.
Po	179	113	−66	170	105	−65	N.S.	N.S.	*	N.S.
Pt	215 (100)	177 (100)	−38 (0)	203 (100)	177 (100)	−25 (0)	N.S.	N.S.	N.S.	N.S.

[a] See Section 2.6.
[b] Before burning: bb.
[c] Directly after burning: ab.
[d] N.S.: non-significant.
[e] Values in brackets are percentage of Pt.
* $P < 0.1$.
** $P < 0.05$.
*** $P < 0.01$.

that the eroded nutrients mainly originated from this topsoil layer (Hoang Fagerström, 2000).

4.2. Fallow versus cropping treatments

The fallow period (TepFa and NaFa) gave less nutrient losses through erosion and crop removal than the cropping period (Mono, TepAl, TepMu). The increase in labile plus moderately labile organic P in the fallow treatments may be explained by a re-conversion of inorganic P to organic P. According to Magid et al. (1996), a 20–30% increase in organic P was seen during 8 years of bush fallow, with most changes in organic P-contents observed in the NaOH extractable fraction. The increase of the labile organic P-fraction (Bicarb-Po) combined with the decrease of the moderately labile organic P-fraction (NaOH-Po) under TepFa and NaFa compared to Mono, TepAl, and TepMu may possibly indicate that TepFa and NaFa could optimise P cycling by re-allocating P from less labile P-pools to more labile ones. This pattern indicates the importance of the fallow period in optimising the nutrient balance and cycling.

4.3. Tephrosia fallow versus natural fallow

The significant increase in N accumulated in the above-ground part of TepFa compared to NaFa and the increase in total N in the 0–5 cm soil layer of TepFa compared to NaFa could due to the N fixation ability of *Tephrosia* (Gichuru, 1991). However, all N gained in TepFa compared to N in NaFa did not return to the soil. Part of it was exported from the field as fuel-wood.

The decrease of the NaOH-Po pool in TepFa compared to NaFa indicated that this P-pool was depleted by *Tephrosia* due to a higher P uptake. It has been frequently observed that NaOH-Po in weathered tropical soils represents a highly available P-pool despite its limited chemical solubility (Tiessen et al., 1992). There was also a trend in the present study (although not significant) that the amount of Bicarb-Pt in TepFa was higher than in NaFa. This might indicate that *Tephrosia* fallow could better optimise P cycling by reallocating P from less labile P-pools to more labile ones. Bicarb-Pi was released to a greater extent in TepFa than in NaFa after burning, which may depend on different fire intensities in the two fallow systems. According to Ketterings (1999), phosphorus availability showed a decrease where the fire intensity had been highest, whereas a gain was detectable where burning had been less intensive.

4.4. External or internal Tephrosia mulch versus non-mulch

Continuous cropping with external or internal *Tephrosia* mulch (TepAl and TepMu) had less N and P losses through erosion than the non-mulched cropping system (Mono). The erosion control could be clearly seen only during the second experimental year (1997). This agreed with findings from other experimental sites in the area and was explained by the fact that *Tephrosia* obtains its maximum growth in the second year after planting (Oyen, 1997). Therefore, the hedgerow was probably more fully established and the amount of pruned material of *Tephrosia* was also larger during the second year. This suggests that the study could have been carried out on for another couple of years. The TepAl treatment seemed to prevent run-off water more effectively than TepMu. However, no significant differences in soil or nutrient losses were found for the two systems. This shows that TepAl was more effective than TepMu in improving water penetration and/or in increasing the water demand, but not in preventing soil loss.

In TepAl and TepMu, the N and P inputs to the soil by internal cycling and external mulch additions were 2–3 times and 1–2 times higher, respectively, than those needed to compensate for the N and P removals through crop export. This was obviously due to a sufficient quantity and quality of the pruned biomass of *Tephrosia* used as mulching material. Pruned biomass had an N-content of 34 g kg^{-1} DM. This content was larger than the 25 g N kg^{-1} DM recommended for organic material to be used as green manure. This recommendation is based on the observation that plant tissue concentrations ranging from 18 to 22 g N kg^{-1} represent the critical threshold for the transition from net N immobilisation to net N mineralisation (Palm et al., 1997). The N contribution from the mulching material was 100 kg ha^{-1} (in TepAl) and 118 kg ha^{-1} (in TepMu) for a 2-year-period. These amounts are larger than the 40 kg N ha^{-1} year^{-1} considered to be the absolute minimum green manure N recommended by Giller et al. (1997) for African conditions to obtain a significant effect on cereal yields. However, the external mulch system (TepMu) required an extra 20% of planted area for producing the required amount of mulching materials.

After the two experimental years, total N in the 0–5 cm soil layer of the mulched systems (TepAl and TepMu) had increased, and more so in TepAl than in TepMu. The TepAl treatment could also maintain the P-pool level in the topsoil, probably due to a lower P export through crop removal, while the NaOH-Po pool was significantly depleted in the TepMu treatment. The significant correlation between the decline in the NaOH-Po pool in the 0–5 cm soil layer and the grain P accumulation in the three continuous cropping systems (Mono, TepAl, and TepMu) could explain the depletion of the P-pools, which was particularly expressed in the TepMu treatment. Hedley et al. (1994) showed that most of the P taken up by upland rice cultivars, in both P-fertilised and unfertilised soil, was solubilized from a NaOH-extractable pool by root-induced changes. The efficient P uptake in TepMu may be partly explained by improved moisture conditions due to the mulch layer in this treatment (Ball-Coelho et al., 1993). The external mulch application was not enough to counterbalance the removal of P through the harvest of upland rice, and as a consequence the soil NaOH-P pool was depleted at least on a short-term basis. For long-term sustainability, mulching in combination with mineral P fertiliser would be a more optimal fertilisation strategy (Palm et al., 1997). This would require that both the Vietnamese government and the farmers in the area give a high priority to a sustained soil fertility in these uplands.

5. Conclusions

The *Tephrosia* systems (TepFa, TepAl, TepMu) prevented nutrient losses by erosion effectively. *Tephrosia* fallow (TepFa) gave positive N and P balances, increased soil N and tended to positively affect the release of labile soil P. The continuous cropping with external and internal *Tephrosia* mulch (TepAl, TepMu) improved the N and P balance due to erosion control by hedgerows and mulching practice. These systems could supply enough N and P to meet crop requirements during a 2-year-period. However, the external mulch system (TepMu), could not fully sustain the P level in the topsoil, probably due to a high P uptake in this treatment.

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References

Anonymous, 1994a. Svensk Standard, SS-ISO 10390. Markundersökningar—Bestämning av pH. SIS, Stockholm.

Anonymous, 1994b. Svensk Standard, SS-ISO, 11260. Soil quality—determination of effective cation exchange capacity and base saturation level using barium chloride solution. SIS, Stockholm.

Ball-Coelho, B., Salcedo, I.H., Tiessen, H., Stewart, J.W.B., 1993. Short- and long-term phosphorus dynamics in a fertilized ultisol under sugarcane. Soil Sci. Soc., Am. J. 57, 1027–1034.

Buresh, R.J., Smithson, P.C., Hellums, D.T., 1997. Building soil phosphorus capital in Africa. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. Soil Science Society of America, Inc., American Society of Agronomy, Inc., Wisconsin, pp. 111–149.

Chao-Yong, Luh Huang, Schulte, E.E., 1985. Digestion of plant tissue for analysis by ICP emission spectroscopy. Communication in soil science. Plant Anal. 16 (9), 943–958.

Do Dinh, Sam, 1994. Shifting Cultivation in Viet Nam: Its Social, Economic and Environmental Values Relative to Alternative Land Use. IIED Forestry and Land Use Series, No. 3, Hanoi.

Fagerström, M.H., 1998. Shifting cultivation and agroforestry research in the tropics: a case study in northern Viet Nam. In: Berger, A. (Ed.), Twice Humanity Implications for Local and Global Resource Use. The Nordic Africa Institute and Forum for Development Studies, Uppsala, Chapter 8, pp. 101–116.

FAO, 1990. Guidelines for Soil Profile Description. Rome.

Gichuru, M.P., 1991. Residual effects of natural bush, *Cajanus cajan* and *Tephrosia candida* on the productivity of an acid soil in south–eastern Nigeria. Plant and Soil 134, 32–36.

Gijsman, A.J., Oberson, A., Tiessen, H., Friesen, D.K., 1996. Limited applicability of the CENTURY model to highly weathered tropical soils. Agron. J. 88, 894–903.

Giller, K.E., Cadisch, G., Ehaliotis, C., Adam, E., Sakala, W.D., Mafongoya, P.L., 1997. Building soil nitrogen capital in Africa. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. Soil Science Society of America, Inc., American Society of Agronomy, Inc., Wisconsin, pp. 151–192.

Hoang Fagerström, M.H., 2000. Agroforestry systems in northern Viet Nam with *Tephrosia candida* as an alternative to short-fallow crop rotations. Doctoral thesis, Swedish University of Agricultural Sciences, Uppsala.

Hoang Fagerström, M.H., van Noordwijk, M., Thai Phien, Nguyen Cong Vinh, 2001. Innovations within upland rice-based systems in northern Viet Nam with *Tephrosia candida* as fallow species, hedgerow, or mulch: Net returns and farmer's response. Agric. Ecosys. Environ., in press.

Hedley, M.J., Kirk, G.J.D., Santos, M.B., 1994. Phosphorus efficiency and the forms of soil phosphorus utilised by upland rice cultivars. Plant and Soil 158, 53–62.

Hedley, M.J., Stewart, J.W.B., Chauhan, B.S., 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation particles and laboratory incubations. Soil Sci. Soc., Am. J. 46, 970–976.

Kadiata, B.D., Mulongoy, K., Isirimah, N.O., Amakiri, M.A., 1996. Screening woody and shrub legumes for growth, nodulation and nitrogen-fixation potential in two contrasting soils. Agroforestry Systems 33, 137–152.

Kang, B.T., 1997. Alley cropping—soil productivity and nutrient recycling. Forest Ecol. Manage. 91, 75–82.

Ketterings, Q.M., 1999. Is slash-sell wood and burn a viable alternative to slash-and-burn in Sumatra? II. Burn efficiencies and short-term soil fertility changes. In: Fire as a Land Management Tool in Sepunggur, Sumatra, Indonesia. Can farmers do without it? Ph.D. thesis, The Ohio State University.

Magid, J., Tiessen, H., Condron, L.M., 1996. Dynamics of organic phosphorus in soils under natural and agricultural ecosystems. In: Piccolo, A. (Ed.), Humic Substances in Terrestrial Ecosystems. Elsevier, Amsterdam, pp. 429–466.

Nair, P.K.R., 1993. An Introduction to Agroforestry. Kluwer, Dordrecht.

Nguyen Tu, Siem, Thai, Phien, 1993. *Tephrosia candida*—a soil ameliorator plant in Viet Nam. Contour 1, 27–28.

Oyen, L.P.A., 1997. *Tephrosia candida* (Roxb.) D.C. In: Faridah Hanum, I., van der Maesen, L.J.G. (Eds.), Plant Resources of South–East Asia. Auxiliary Plants. No. 11, Backhuys Publishers, Leiden, The Netherlands, pp. 244–246.

Palm, C.A., 1995. Contribution of agroforestry trees to nutrient requirements of intercropped plants. Agroforestry Systems 30, 105–124.

Palm, C.A., Myers, R.J.K., Nandwa, S.M., 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), Replenishing Soil Fertility in Africa. Soil Science Society of America, Inc., American Society of Agronomy, Inc., Wisconsin, pp. 193–217.

Sanchez, P.A., 1994. Tropical soil fertility research: towards the second paradigm. ICRAF, Nairobi, Kenya, 15 p.

Sanchez, P.A., Palm, C.A., 1996. Nutrient cycling and agroforestry in Africa. Unasylva 185 (47), 24–28.

Schroth, G.S., Kolbe, D., Pity, B., Zech, W., 1995. Searching for criteria for the selection of efficient tree species for fallow improvement, with special reference to carbon and nitrogen. Fertilizer Res. 42, 297–314.

Smaling, E., 1993. An agroecological framework for integrated nutrient management with special reference to Kenya. Doctoral thesis, Wageningen Agricultural University, The Netherlands.

Snapp, S.S., Mafongoya, P.L., Waddington, S., 1998. Organic matter strategies for integrated nutrient management in smallholder cropping systems of southern Africa. Agric. Ecosys. Environ. 71, 158–200.

Swedish Standard SS 028127, 1984. Water investigations—determination of total phosphorous in water—digestion with peroxodisulphate. SIS, Stockholm.

Thai Phien, Tu Siem, 1996. Management of sloping lands for sustainable agriculture in Vietnam. In: Sajjapongse, A., Leslie, R.N. (Eds.), The Management of Sloping Lands in Asia (IBSRAM/ASIALAND). Network Document No. 20. Bangkok. Thailand: IBSRAM, pp. 278.

Tiessen, H., Stewart, J.W.B., Cole, C.V., 1984. Pathway of phosphorus transformations in soils of differing pedogenesis. Soil Sci. Soc., Am. J. 48, 853–858.

Tiessen, H., Salcedo, I.H., Sampaio, E.V.S.B., 1992. Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid north–eastern Brazil. Agric. Ecosys. Environ. 38, 139–151.

van Noordwijk, M., 1999. Nutrient Cycling in Ecosystems versus Nutrient Budget of Agricultural Systems. In: Smaling, E.M.A., Oenema, O., Fesco, L.O. (Eds.), Nutrient Disequilibria in Agroecosystems. CAB International, Wallingford, Oxon, UK, pp. 1–25.

van Reeuwijk, L.P., 1993. Procedures for Soil Analysis. ISRIC, Wageningen, pp. 3-1–3-12.

Watanabe, F.S., Olsen, S.R., 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts. Soil Sci. Soc., Am. Proc. 29, 677–678.

Young, A., 1985. Soil Aspects of the Forestry Plantation Programme for the Vinh Phu Pulp and Paper Mill, Viet Nam. ICRAF, Nairobi, 92 pp.