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ORIGINAL PAPER

Impact of planted fallows and a crop rotation on nitrogen mineralization and phosphorus and organic matter fractions on a Colombian volcanic-ash soil

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Abstract Soil fertility replenishment is a critical factor that many farmers in the tropical American hillsides have to cope with to increase food crop production. The effect of three planted fallow systems (*Calliandra houstoniana*-CAL, *Indigofera zollingeriana*-IND, *Tithonia diversifolia*-TTH) and a crop rotation (maize/beans-ROT) on soil nitrogen mineralization, organic matter and phosphorus fractions was compared to the usual practice of allowing natural regeneration of native vegetation or natural fallow management (NAT). Studies were conducted on severely degraded Colombian volcanic-ash soils, 28 months after fallow establishment, at two on-farm experimental sites (BM1 and BM2) in the Cauca Department. *Tithonia diversifolia* had a significantly higher contribution to exchangeable Ca, K and Mg as well as B and Zn; the order of soil nutrient contribution was TTH > CAL > IND > NAT > ROT. On the other hand, lND had significantly higher soil NO_3^-–N at both experimental farms as compared to all the other fallow system treatments. For the readily available P fraction, CAL and ROT had significantly higher H_2O–Po and resin-Pi, respectively, in the 0–5 cm soil layer; whereas TTH showed significantly higher values for both H_2O–Po and resin-Pi in the 5–10 cm soil layer. Significant effects were observed on the weights of the soil organic matter fractions which decreased in the order LL (Ludox light) >LM (Ludox intermediate) >LH (Ludox heavy). *Indigofera zollingeriana* showed greater C, N and P in the soil organic matter fractions than all the other fallow treatments, with NAT having the lowest values. It is concluded that planted fallows can restore soil fertility more rapidly than natural fallows.

Keywords *Calliandra houstoniana* · *Indigofera zollingeriana* · Nitrogen mineralization potential · Phosphorus fractions · Planted fallows · Residual effect · Soil organic matter fractions · *Tithonia diversifolia* · Volcanic-ash soil

Introduction

In order to achieve food security and reduce poverty in the tropical American hillsides, soil fertility maintenance and improvement must take very high priority. This would go a long way in ensuring sustained and increased food crop

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production in these usually extensive agroecosystems. The hillside agroecosystems in the Cauca Department in Colombia are dominated by volcanic-ash soils, which are shallow, nutrient deficient and prone to severe erosion and subsequent degradation (CIAT 2001). These areas, like many others in the tropics, are characterized by increasing human and livestock populations that are exerting increased pressure on the land. This has undermined the ability of shifting cultivation, the dominant traditional agricultural system practiced by the farmers here, to maintain and restore soil fertility. Although fallows have historically played an important role in maintaining the productivity of farming systems (Loomis 1984), traditional fallowing has become insufficient in restoring soil fertility since the duration and intensity of fallowing has been drastically reduced over the years. This shortening of traditional fallows, combined with little or no use of fertilizers, has had negative consequences on agricultural productivity and agroecosystem stability because of nutrient mining (Smaling et al. 1997). Nye and Greenland (1960) have reported that natural fallows have long been used to overcome soil fertility depletion that results from continuous cropping with no external inputs. The fallow period may vary from 5 to 20 years. Losses of mineral nutrients during the cultivation phase, through runoff, erosion, leaching and crop removal, can no longer be restored by short 1–5 year periods of natural bush fallow (Brady 1996). This situation requires soil nutrient replenishment options. When access to organic and inorganic fertilizers is limited, then improved fallows with legume species deliberately planted in order to achieve the aims of natural fallow within a short time, becomes an attractive option (Prinz 1986; Barrios et al. 1997).

Planted fallows have been recognized as an appropriate agroforestry technology that can be used by many rural farmers because of their low risk and relatively low cost for establishment with proven potential to generate additional products in the short run (i.e. firewood) while improving soil fertility (Barrios et al. 2005). Fallowing plays several roles within a farming system, as it can reduce agricultural weeds and pests and improves soil physical, chemical and biological properties. Planted fallows are thus a permanent environmental production system in which natural vegetation is intentionally replaced by planted and managed, fast growing tree, shrub or herbaceous species grown in rotation with cultivated crops (van Noordwijk 1999). Therefore, planted fallows can optimize nutrient cycling and efficiently utilize external nutrient inputs (Sanchez 1994). Planted fallows can restore agricultural productivity more rapidly than natural fallows and have been suggested as a potential solution to declining soil productivity caused by shortened natural fallow periods (Tian et al. 1999). Among other factors, the beneficial effects of planted fallows depend on fallow species, fallow duration, soil type and climate (Adejuwon and Adesina 1990).

Some studies have been carried out on the residual effects of planted fallows on subsequent crops (Adejuwon and Adesina 1990; Drechsel et al. 1996; Barrios et al. 1998; Kwesiga et al. 1999). However, very few studies have investigated the residual effects of planted fallows, simultaneously, on soil nitrogen mineralization, organic matter and phosphorus fractions, especially on volcanic-ash soils. In the same experimental site as in this study, Phiri et al. (2001) showed that planted fallows, one year after establishment, can provide soil organic matter that boosts soil fertility through improved nitrogen and phosphorus recycling. It is of interest in this study to define how transient or permanent this phenomenon is, in the longer term.

The objective of our study was to assess the effect of four planted fallow systems and a crop rotation on soil nitrogen mineralization, organic matter and phosphorus fractions at 28 months after establishment in a volcanic-ash soil. We tested four hypotheses. These include:

(1) Planted fallows would restore soil fertility more rapidly than natural fallows and observed differences in soil characteristics would decrease with depth;
(2) Planted fallows contributing high quality residue inputs would generate a greater proportion of organic matter fractions contributing to short-term N availability through N mineralization than those providing low quality residue inputs;

(3) Planted fallows contributing high quality residue inputs would generate a greater proportion of P fractions contributing to short-term P availability than those providing low quality residue inputs; and
(4) The duration of increased soil fertility (residual effect) would be longer following planted fallows producing low quality residue inputs than those producing high quality residue inputs.

Materials and methods

Description of the study area

This study was conducted at two farms in Pescador village, located in the Andean hillsides of the Cauca Department, southwestern Colombia (2°48′ N, 76°33′ W) at 1500 m above sea level. They represented two typical small farms, on a common soil type, just prior to traditional fallow management following 3 years of cassava cultivation at the end of the cropping cycle (Barrios and Cobo 2004). The area has a mean temperature of 19.3°C and a mean annual rainfall of 1900 mm (bimodal). The experiments were started in November 1997 and the fallow period concluded in February 2000.

The soils in the study area are derived from volcanic-ash deposition and are classified as Oxic Dystropepts (Inceptisols) under the USDA soil classification system (Soil Survey Staff 1998), They have medium to fine textures (IGAC 1979), high fragility, low cohesion and shallow humic layers. The soil bulk density was about 0.8 Mg m^{-3}. The soils are acidic (pH (H_2O) = 5.1), have high SOM content (C = 50 mg g^{-1}) and are low in base saturation (1.1 and 2.5 cmol kg^{-1} soil for Al and Ca, respectively). They have high P-sorbing capacity and soil available P is very low due to the high allophane content (52–70 g kg^{-1}) (Gijsman and Sanz 1998).

Experimental treatments and design

In this fallow systems study, we used two leguminous tree fallows; Calliandra (*Calliandra houstoniana* (Mill.) Stan. var. *calothyrsus* (Meisn.) Barn. = CIAT 20400) and Indigofera (*Indigofera zollingeriana* Miq.); and a shrubby fallow, Tithonia (*Tithonia diversifolia* (Hemsl.) A. Gray). Calliandra and Indigofera can withstand frequent pruning, effectively fix N and are well adapted to low night temperatures, seasonal drought and soil acidity (Barrios et al. 2005). Indigofera produces high quality biomass (decomposes rapidly) whereas Calliandra produces low quality biomass (decomposes slowly). This contrast in the experimental design provides the opportunity to study the effect of quality of plant biomass on nitrogen, soil organic matter and phosphorus dynamics and soil fertility improvement potential. Tithonia was used because it grows rapidly and accumulates high concentrations of nutrients in the shoot, especially P in the leaves (Ganunga et al. 1998; Barrios and Cobo 2004).

Experiment BM1 was set up at San Isidro farm in Pescador village as a random complete block (RCB) design with four fallow system treatments and a crop rotation treatment with three replications.

Fallow treatments:

(i) *Calliandra houstoniana* (Mill.) Stan. var. *calothyrsus* (Meisn.) Barney CIAT 20400 (CAL) and
(ii) *Indigofera zollingerana* Miq. (IND) (both CAL and IND are leguminous trees); and
(iii) *Tithonia diversifolia* (HemsL) Gray. (TTH) from the Asteraceae family;
The above three treatments were compared to
(iv) a maize/bean rotational system (ROT); and
(v) a natural fallow system (NAT), that was left to natural regeneration of native vegetation that is the usual practice once agricultural soils become unproductive.

Experiment BM2 was set up at Benizio Velazco farm also in Pescador village. It was also established as a RCB design but due to limited space, it consisted of three fallow system treatments with three field replications. Treatments included CAL, IND and NAT with the same management as in BM1. In both experiments, plot size was 18 × 9 m^2, Pruning management regimes of ‘slash and mulch' were carried out according to local farmers concerns about the growth and productivity of the planted fallow systems. Additional experimental design details can be found in Barrios and Cobo (2004).

Soil sampling and laboratory analytical procedures

Soil samples (0–5, 5–10 and 10–20 cm depths) were collected in March 2000, 28 months after the fallows and rotational crops were planted. Soil sampling was conducted at one month after the fallow period was completed and plant biomass cut and laid on the soil surface (but prior to removal of firewood). Before collecting soil samples, soil surface plant litter was carefully removed. Due to high inherent variability in hillside soils, a composite sample consisting of 50 cores was collected in a grid pattern from each of the 18×9 m^2 plots. Samples were air-dried and visible plant roots removed. The samples were then gently crushed to pass through a 2-mm sieve. The <2 mm fraction was used for all the analyses and fractionation procedures. All laboratory analyses were conducted in duplicate.

Total organic C was determined colorimetrically after wet oxidation with acidified potassium dichromate and external heating (Anderson and Ingram 1993). Total N and P for whole soil were determined by digestion with concentrated sulphuric acid using selenium as a catalyst, followed by colorimetric determination with an auto analyzer (Skalar Sun Plus, the Netherlands). Bray P and exchangeable K were extracted with Bray II solution followed by colorimetric and atomic absorption determination, respectively. Exchangeable Ca and Mg, and Al were extracted with 1 M KCl solution and determined as described in CIAT (1993). Nitrate and ammonium were extracted in 1 M KCl solution and determined by colorimetry with an auto analyzer (Skalar Sun Plus, The Netherlands).

Soil potential N mineralization was determined by anaerobic incubation of whole soil (Anderson and Ingram 1993). Briefly, 10 g of soil were flooded with 25 ml of deionized water and incubated anaerobically for 7 days at 40°C. After incubation, samples were transferred to 125 ml extraction bottles, extracted with 25 ml of 4 M KCl with shaking for 1 h at 150 reciprocations min^{-1}, filtered by gravity using Whatman No. 5 paper, prewashed with de-ionized water and analyzed for NH_4^+–N. Nitrogen mineralization was calculated as the difference in NH_4^+–N between incubated samples and unincubated samples extracted immediately after flooding the soil (Barrios et al. 1996b).

Size-density fractionation of SOM (in the sand-size fraction, 150–2000 μm) was conducted as described by Phiri et al. (2001), Barrios et al. (1996a) and Meijboom et al. (1995), with minor modifications and density separation was done in reverse order. In short, an air-dried soil sample (250 g) was gradually wetted, then flooded with 2 l of water, thoroughly mixed and sieved through two superimposed sieves of 250 μm (at the top) and 150 μm (at the bottom). A jet of water through the top sieve destroyed macroaggregates, and materials retained on the sieves were washed into separate buckets and swirled with water. Through repeated swirling and decantation, the floating macroorganic matter (>150 μm) was separated from mineral material. Swirling and decanting was repeated several times until no floating materials remained. The macroorganic matter on the 150 μm sieve was then placed, and density fractionated, in a silica suspension (Ludox^{TM}, Du Pont) adjusted to 1.13 mg m^{-3}. The floating fraction (Ludox Light fraction, LL) was separated and placed on a drying plate. The remaining fraction in the sieve was then placed in Ludox adjusted to 1.37 mg m^{-3}. The new floating fraction was the Ludox Intermediate fraction (LM), and the non-floating fraction, the Ludox Heavy fraction (LH). All the three fractions were washed with tap water, followed by deionized water, and then dried to a constant weight at 40°C. After weighing, the SOM fractions were ground with a mortar and pestle to <0.3 mm and then analyzed for C, N and P (Carter 1993).

Phosphorus fractionation was carried out by using a reduced (excluding acid extractants) sequential P fractionation procedure as described by Phiri et al. (2001) and Tiessen and Moir (1993), with minor modifications, where 0.5 g sieved (2-mm) soil samples were used. A sequence of extractants with increasing strength

(H_2O, $NaHCO_3$, NaOH and $HClO_4$, respectively) was applied so as to subdivide the total soil-P into inorganic (Pi) and organic (Po) fractions. The following fractions were separated:

(a) Anion exchange resin membranes, in bicarbonate form, were used to extract freely exchangeable Pi, herein called Resin Pi. Potassium persulphate ($K_2S_2O_8$) was used to digest the Po remaining in the water in the resin Pi extraction stage.
(b) Labile Pi and Po sorbed to the soil surface, including some microbial P, was extracted using $NaHCO_3$ (sodium bicarbonate) at 0.5 M and pH = 8.5.
(c) Pi more strongly bound to Fe and Al compounds and associated with humic compounds was extracted using NaOH (sodium hydroxide) at 0.1 M.
(d) $HClO_4$ (perchloric acid) was used to digest and extract the residue containing insoluble Pi and more stable Po forms (residual P).

Total P in the $NaHCO_3$ and NaOH extracts were measured after digestion with $K_2S_2O_8$, and organic P was calculated as the difference between total P and Pi in the $NaHCO_3$ and NaOH extracts, respectively. Total soil-P was determined by the $HClO_4$ digestion method as described by Olsen and Sommers (1982). Inorganic P concentrations in all the digests and extracts were measured colorimetrically by the molybdate-ascorbic acid method as described by Murphy and Riley (1962).

Statistical analysis

Since the design was unbalanced and some of the blocks and treatments were nonorthogonal, the SAS MIXED procedure (PROC MIXED) was used to determine the effect of planted fallow treatments on soil parameters within and between experimental sites BM1 and BM2 (SAS Institute Inc. 1999). Least-squares means (LS-means) were computed for all the treatments/fixed effects. Comparison of the LS-means was done by the BONFERRONI multiple comparison method, which gave various probability values (*P*-values) that were used to determine whether two treatments were significantly different or not. The letters following the LS-means for each treatment were manually generated after ranking them (from the highest to the lowest) and assigned considering the corresponding *P*-values between any two LS-means compared. These letters could not be generated (automatically) by the SAS program because the design was unbalanced. Mention of statistical significance in this study refers to $P < 0.05$.

Results and discussion

Soil chemical characteristics

In experiment BM1, the TTH system treatment generally had higher but not always significantly higher concentrations of soil total C; total P; Bray P; B; Zn; exchangeable K, Ca and Mg; and the lowest concentration of Al in all soil depths (Table 1). The order of soil nutrient contribution was TTH > IND > ROT > CAL > NAT. These results are in agreement with those of Gachengo et al. (1999), Buresh and Niang (1997), Ganunga et al. (1998), Jama et al. (2000) and Phiri et al. (2001). These researchers have shown that Tithonia green biomass has the potential to significantly improve soil fertility through increased nutrient addition and can considerably reduce the levels of exchangeable Al in soils, thereby curbing Al toxicity problems. It is suspected that Tithonia plants may have pumped K, Ca and Mg from the subsoil through its long rooting system as well as the intimate association found with arbuscular mycorrhizal fungi in this and other areas (Sharrock et al. 2004). It is presumed that this high cation uptake by TTH raises soil pH, thereby lowering exchangeable Al. Furthermore, as an organic source of nutrients, Tithonia has been found to be often more effective than urea when applied at the same nitrogen rate because it also adds other plant nutrients, particularly K and micronutrients (Sanchez 2002).

In experiment BM2, there was no significant effect of the fallows on the soil chemical characteristics in all soil depths (Table 1). However, on average, NAT had the highest total organic carbon, total P and B contents. On the other hand, IND had the highest contents of Ca, K, Mg and

Table 1 Influence of planted fallows on some important soil chemical characteristics[#]

Soil depth (cm)	Fallow species or cropping system	Total C	Total P	P (Bray-II)	Ca	K	Mg	Al	B	Zn
		mg kg^{-1}			cmol kg^{-1}					
Experiment BM1										
0–5	*Calliandra houstoniana*	65,683a	680ab	8.16a	2.13b	0.44b	0.50b	2.17a	0.41a	2.62a
0–5	*Indigofera zollingeriana*	64,700a	678ab	10.71a	2.49ab	0.57b	0.71ab	2.08a	0.45a	2.29ab
0–5	Natural fallow	54,083a	532b	7.78a	1.50b	0.38b	0.42b	2.18a	0.40a	2.38a
0–5	Maize/bean rotation	69,700a	774a	9.87a	2.56ab	0.43b	0.49b	1.73a	0.42a	1.89b
0–5	*Tithonia diversifolia*	70,383a	781a	10.57a	3.63a	1.14a	1.49a	1.09a	0.47a	2.61a
5–10	*Calliandra houstoniana*	61,700ab	631a	7.93a	1.53ab	0.30b	0.34a	3.00a	0.38a	2.71a
5–10	*Indigofera zollingeriana*	60,900ab	593ab	9.77a	1.83ab	0.40ab	0.53a	2.84a	0.38a	2.17b
5–10	Natural fallow	49,367b	452b	6.65a	1.20b	0.32b	0.36a	2.50ab	0.42a	2.63ab
5–10	Maize/bean rotation	66,667a	696a	8.44a	2.02ab	0.32b	0.39a	2.38ab	0.40a	1.79b
5–10	*Tithonia diversifolia*	64,683ab	723a	8.71a	2.72a	0.81a	1.11a	1.46b	0.42a	2.47ab
10–20	*Calliandra houstoniana*	56,650a	564a	6.02a	1.33a	0.21a	0.26a	3.04a	0.38a	2.43a
10–20	*Indigofera zollingeriana*	54,733a	557a	8.01a	1.55a	0.28a	0.35a	2.46a	0.31a	2.00ab
10–20	Natural fallow	47,233a	481a	5.39a	1.17a	0.23a	0.26a	2.90a	0.27a	2.40a
10–20	Maize/bean rotation	60,400a	553a	5.66a	1.42a	0.23a	0.26a	2.50a	0.35a	1.70b
10–20	*Tithonia diversifolia*	60,133a	645a	6.23a	2.21a	0.54a	0.80a	2.09a	0.42a	2.41a
Experiment BM2										
0–5	*Calliandria houstoniana*	69,483a	530a	3.05a	2.76a	0.50a	0.75a	0.57a	0.36a	1.83a
0–5	*Indigofera zollingeriana*	63,883a	526a	2.92a	3.14a	0.66a	0.94a	0.38a	0.34a	2.58a
0–5	Natural fallow	72,933a	584a	2.91a	3.07a	0.64a	0.84a	0.46a	0.41a	2.02a
5–10	*Calliandra houstoniana*	62,750a	419a	2.40a	2.23a	0.28a	0.42a	0.75a	0.23b	1.38a
5–10	*Indigofera zollingeriana*	58,967a	486a	2.42a	2.60a	0.40a	0.55a	0.51a	0.22b	1.99a
5–10	Natural fallow	68,950a	479a	2.52a	2.27a	0.38a	0.48a	0.59a	0.33a	1.53a
10–20	*Calliandra houstoniana*	58,450a	375a	1.86a	1.60a	0.18a	0.29a	0.63a	0.19a	1.19a
10–20	*Indigofera zollingeriana*	54,333a	361a	1.61a	1.81a	0.23a	0.37a	0.60a	0.18a	1.82a
10–20	Natural fallow	65,167a	390a	1.45a	1.67a	0.23a	0.31a	0.68a	0.21a	1.23a

[#] For a given soil nitrogen parameter and depth, LS-means within a column followed by the same letter(s) are not statistically significantly different, using the BONFERRONI multiple comparison method based on probability values (P-values) at $\alpha = 0.05$; Total C = total soil carbon content; Total P = total soil phosphorus content as determined by digestion with concentrated sulphuric acid (see section on soil sampling and laboratory analytical procedures); P(Bray-II) = available phosphorous by the Bray and Kutz No. 2 method; Ca = calcium; K = potassium; Mg = magnesium; Al = aluminium, B = boron; Zn = zinc

the lowest content of Al. It is well known that given enough time, the natural fallow has the potential to regenerate the natural soil fertility in this relatively less fertile experimental site. At both experimental sites, there was a significant decrease of nutrients with increasing soil depth ($P < 0.0001$).

Soil N availability

The residual effect of planted fallows was significant for soil nitrate but not for soil total N, ammonium-N and nitrogen mineralization potential. *Indigofera zollingeriana* had significantly higher values for nitrate (NO_3^-–N) at both sites and at all soil depths as compared to all other fallow treatments (Table 2). In experimental site BM1, the trend was IND > CAL > TTH > NAT > ROT whereas in experimental site BM2, the trend was IND > CAL > NAT. It is likely that the IND system treatment has shown potential to increase nitrate availability in volcanic-ash soils because of Indigofera's fast decomposition and nutrient release rates as reported by Cobo et al. (2002a, b). These relatively higher values could also be partly attributed to the large populations of the endogeic earthworm *Pontoscolex corethrurus*, known to enhance soil nitrogen mineralization, that were observed in IND by Barrios et al. (2005). These findings are consistent with those of Barrios et al. (2005) who have observed that Indigofera and Calliandra trees can effectively fix nitrogen and are well adapted to the soil acidity of this Colombian hillside environment.

Table 2 Influence of planted fallows on soil nitrogen dynamics[#]

Soil depth (cm)	Fallow species or cropping system	Total N mg kg^{-1}	NO$_3^-$–N	NH$_4^+$–N	PNM mg N kg^{-1} day^{-1}
Experiment BM1					
0–5	*Calliandra houstoniana*	4,940a	29.5b	18.0a	4.20a
0–5	*Indigofera zollingeriana*	4,843a	44.6a	22.1a	4.56a
0–5	Natural fallow	4,076a	20.1bc	20.1a	4.29a
0–5	Maize/bean rotation	5,324a	16.0bc	19.5a	4.50a
0–5	*Tithonia diversifolia*	5,351a	25.8bc	19.4a	3.98a
5–10	*Calliandra houstoniana*	5,148a	25.9b	14.5b	4.13a
5–10	*Indigofera zollingeriana*	4,482a	40.3a	15.3ab	3.47a
5–10	Natural fallow	3,841a	18.1b	17.6ab	3.52a
5–10	Maize/bean rotation	4,893a	17.8b	19.0a	3.91a
5–10	*Tithonia diversifolia*	5,218a	20.3b	16.4ab	4.23a
10-20	*Calliandra houstoniana*	4,390a	24.2ab	16.0a	2.98a
10–20	*Indigofera zollingeriana*	3,870a	36.3a	13.3a	2.98a
10–20	Natural fallow	3,541a	15.5b	16.4a	3.23a
10–20	Maize/bean rotation	4,135a	16.6b	14.4a	2.80a
10–20	*Tithonia diversifolia*	4,543a	17.5b	17.4a	3.25a
Experiment BM2					
0–5	*Calliandria houstoniana*	5,435a	33.5b	19.0a	2.95a
0–5	*Indigofera zollingeriana*	5,534a	54.0a	22.6a	3.31a
0–5	Natural fallow	5,604a	10.8c	19.2a	2.71a
5–10	*Calliandra houstoniana*	4,859a	21.6b	18.9a	3.31a
5–10	*Indigofera zollingeriana*	4,673a	36.4a	21.3a	2.90a
5–10	Natural fallow	5,497a	9.33c	20.0a	3.12a
10–20	*Calliandra houstoniana*	4,556a	18.2a	19.5a	2.15a
10–20	*Indigofera zollingeriana*	4,574a	23.3a	19.5a	2.07a
10–20	Natural fallow	4,745a	6.16b	18.1a	2.32a

[#] For a given soil nitrogen parameter and depth, LS-means within a column followed by the same letter(s) are not statistically significantly different, using the BONFERRONI multiple comparison method based on probability values (*P*-values) at $\alpha = 0.05$; Total N = total soil nitrogen; NO$_3^-$–N = nitrate-N; NH$_4^+$–N = ammonium–N; PNM = nitrogen mineralization potential

Soil total N, as well as total soil C, change very slowly over time and thus their potential to detect short term changes in management is limited (Barrios et al. 1996a) and our results showing no significant results among system treatments studied corroborate such findings also in volcanic ash soils. Although Tithonia has consistently been known to promote higher N mineralization potential in soils (Ganunga et al. 1998; Jama et al. 2000), and this has been attributed to its high quality green leaf biomass that is rich in nutrients and decomposes rapidly, in this study no significant differences were found among system treatments. In this study, however, N mineralization was studied under laboratory conditions. This could lead to an underestimation of potential N mineralization because it does not account for the flush of N mineralization that occurs when dry soil is rewetted in the field (Cabrera 1993).

In a study on changes in soil properties following improved fallow systems in eastern Zambia, Chirwa et al. (2004) reported that nitrogen contribution and improvement in soil physical properties were significant after one year of fallow period but declined thereafter. This observation agrees with the findings in this experiment. It also agrees with the findings of Phiri et al. (2001) who found significant differences in soil N following one year of fallow establishment. However, it contrasts with findings by Barrios et al. (1997) in eastern Zambia where *Sesbania sesban* improved fallows still generated significant improvements in soil N after 2 and 3 years of fallow establishment. It is probable that differences in soil type, climatic conditions, tree species and tree/shrub management regimes used could account for some of these conflicting results.

There was a general significant decrease in total N, NO_3^-–N, NH_4^+–N and N mineralization potential with increasing soil depth ($P < 0.0001$). Since the soils were sampled at the beginning of the rainy season (in April), it is possible that the mobile NO_3^-–N was not yet leached to the lower soil layers (Maroko et al. 1998). Organic matter being a major source of plant available N, decreasing SOM with depth could also be a possible explanation for this trend of results.

Soil phosphorus fractions

Phosphorus exists in soils in different chemical forms and pools (Fixen and Grove 1990). Phosphorus acquisition is, however, strongly related to soil moisture, temperature and texture because this nutrient is of limited mobility in the soil, moving to the root surface via diffusion in water films on particle surfaces. For P fractions and fractionation procedures to come closer to the real-world soil management systems, there is need for partitioning soil P fractions into three discrete pools i.e. the readily available (biologically available and easily mineralizable), the moderately resistant (moderately and reversibly available) and the stable residual (sparingly available and highly recalcitrant/resistant) P as described by Guo and Yost (1998). This is the basis of P transformations and cycling in soils. Phosphorus transformations in soils involve complex mineralogical, chemical and biological processes and knowledge of these transformations is essential to understand P behavior in soils (Oberson et al. 2001).

In experiment BM1, significantly higher H_2O–Po in the 0–5 cm soil depth was found in CAL, whereas ROT showed significant results for resin-Pi, when compared with that for IND at the same depth. In the 5–10 cm depth, TTH showed significant results for both H_2O–Po and resin-Pi (Table 3). Results for the 10–20 cm soil depth were not significant. These findings contrasts with previous research results at the same experiment by Phiri et al. (2001) where TTH clearly showed superior performance in terms of soil P availability. *Tithonia diversifolia* produced higher nutrient yields, especially of P, as compared to other species, 6 and 12 months after planting in western Kenya (Niang et al. 2002). The better performance of the fallows was attributed to efficient nutrient accumulation and cycling, high quality biomass and site adaptability (Barrios and Cobo 2004).

Surprisingly, compared with all the other fallow treatments, NAT results for $NaHCO_3$–Pi, $NaHCO_3$–Po and $NaHCO_3$–Pt were significantly higher than those for TTH in the 0–5 cm soil depth, though the results for the 5–10 and 10–20 cm soil depths were not significant (Table 3). This could probably be due to the fact that young natural fallows (< 3 years) usually have high rates of photosynthesis, rapid increases in leaf area and leaf biomass, and higher tissue concentrations than older secondary vegetation (Szott and Palm 1996). These characteristics result in high rates of nutrient demand and accumulation, litter production and soil cover establishment (Szott et al. 1999). Thus, they help to reduce nutrient losses by leaching and runoff and to mobilize P from non-readily available forms in the soil. In experiment BM2, there was no overall significant residual effect of planted fallows on the readily available P fractions in the soils. However, on average, NAT had higher values for H_2O–Po, resin–Pi, $NaHCO_3$–Pi, $NaHCO_3$–Po and $NaHCO_3$–Pt at all soil depths.

In both experiments, there was a significant decrease in H_2O–Po, resin–Pi, $NaHCO_3$–Pi, $NaHCO_3$–Po and $NaHCO_3$–Pt with increasing soil depth ($P < 0.05$). This could be attributed to the high soil organic matter content in the topsoil layers of these soils as reported by Phiri et al. (2001). Presumably, the presence of deep-rooted planted fallows resulted in P from deeper soil layers being pumped into the topsoil layers.

Table 4 shows the impact of planted fallow systems on moderately resistant and stable (residual) P fractions. The moderately resistant P fraction mostly includes NaOH–Pi and NaOH–Po, which normally become available in the medium term i.e. from a few months to years (Cross and Schlesinger 1995). In experiment BM1, results for the moderately resistant P fraction in the 0–5, 5–10 and 10–20 cm soil layers were higher for NAT, TTH and IND respectively, though the results were not statistically significant, except for the significant difference between

Table 3 Influence of planted follows on the readily (biologically) available P fractions in soils[#]

Soil depth (cm)	Fallow species or cropping system	H_2O–Po mg kg^{-1}	Resin–Pi	$NaHCO_3$–Pi	$NaHCO_3$–Po	$NaHCO_3$–Pt
Experiment BM1						
0–5	*Calliandra houstoniana*	3.51a	10.48ab	21.8ab	30.5ab	52.2ab
0–5	*Indigofera zollingeriana*	1.95b	6.15b	20.8ab	31.8ab	52.6ab
0–5	Natural fallow	2.28ab	8.78ab	24.1a	36.0a	60.1a
0–5	Maize/bean rotation	2.62ab	10.74a	20.2ab	28.9ab	49.lab
0–5	*Tithonia diversifolia*	1.50b	6.67ab	16.0b	25.7b	41.7b
5–10	*Calliandra houstoniana*	1.83bc	5.49ab	16.4a	23.7a	40.1a
5–10	*Indigofera zollingeriana*	1.28bc	4.05b	17.4a	27.4a	44.8a
5–10	Natural fallow	2.39ab	5.63ab	17.4a	26.3a	43.6a
5–10	Maize/bean rotation	0.94c	4.84b	17.9a	29.2a	47.1a
5–10	*Tithonia diversifolia*	3.40a	9.43a	22.1a	27.7a	49.9a
10–20	*Calliandra houstoniana*	1.84a	4.31a	14.7a	23.1a	37.7a
10–20	*Indigofera zollingeriana*	1.46a	2.56a	13.2a	21.6a	34.8a
10–20	Natural fallow	1.78a	4.10a	12.0a	19.6a	31.6a
10–20	Maize/bean rotation	1.39a	4.44a	13.1a	22.3a	35.4a
10–20	*Tithonia diversifolia*	1.67a	4.16a	13.4a	20.6a	34.0a
Experiment BM2						
0–5	*Calliandra houstoniana*	0.82b	2.50a	11.0a	16.6b	27.6b
0–5	*Indigofera zollingeriana*	0.61b	2.69a	11.8a	18.2ab	30.0ab
0–5	Natural fallow	1.25a	3.90a	13.8a	19.8a	33.6a
5–10	*Calliandra houstoniana*	0.51a	1.99a	10.0a	15.6a	25.6a
5–10	*Indigofera zollingeriana*	0.82a	1.80a	9.40a	16.2a	25.6a
5–10	Natural fallow	0.72a	1.99a	10.6a	16.2a	26.8a
10–20	*Calliandra houstoniana*	0.51a	1.35a	6.60a	12.2a	18.8a
10–20	*Indigofera zollingeriana*	0.61a	1.35a	6.00a	12.4a	18.4a
10–20	Natural fallow	0.51a	1.42a	6.60a	13.4a	20.0a

[#] For a given soil nitrogen parameter and depth, LS-means within a column followed by the same letter(s) are not statistically significantly different, using the BONFERRONI multiple comparison method based on probability values (P-values) at $\alpha = 0.05$; H_2O–Po = water extractable organic P; Resin–Pi = resin extractable inorganic P; $NaHCO_3$–Pi = sodium bicarbonate extractable inorganic P; $NaHCO_3$–Po = sodium bicarbonate extractable organic P; $NaHCO_3$–Pt = sodium bicarbonate extractable total P

NAT and TTH in the 0–5 cm soil layer. Barrios et al. (2004) have reported large populations of the endogeic earthworm *Pontoscolex corethrurus* under IND treatments, and so there is a possibility that in this study, there was movement of organic P by earthworms to the deeper soil layers. Maintenance of active earthworm populations can be favourable to nutrient cycling and crop production in low-input tropical agroecosystems (Pashanasi et al. 1996). These mixed results show that there was no clearly dominant fallow treatment as far as provision of moderately resistant P is concerned. However, the situation was slightly different in experiment BM2 where NAT had the highest values for this P fraction in all the soil layers, despite the fact that the results were not statistically significant. Tiessen et al. (1992) found a significant improvement in NaOH-extractable P after nine years of fallow, which leads us to the argument that probably the time (28 months of fallowing) was too short to get any significant results for this fraction.

The residual P fraction showed a similar trend to that of the moderately resistant fraction in both experiments. This fraction comprises of stable humus, highly insoluble Pi forms and the more stable Po forms as described by Hedley et al. (1982). It becomes available in the longer term, may be after several cropping cycles.

Total Pi, total Po, total P (Pi + Po) and total Po as a percentage of total soil P were generally not significantly affected by the planted fallows in both experiments (Table 4). These results are consistent with those of Maroko et al. (1999) who observed that land-use systems had no effect on extractable P fractions in tropical soils. Of special

Table 4 Influence of planted fallows on moderately resistant and stable (residual) P fractions in soils[#]

Soil depth (cm)	Fallow species or cropping system	NaOH–Pi	NaOH–Po	NaOH–Pt	Residual P	Total Pi	Total Po	Total P (Pi + Po)	Total Po as % age of total soil P
		mg kg^{-1}							%
Experiment BM1									
0–5	*Calliandra houstoniana*	215ab	202a	417ab	292a	539ab	236a	775ab	30a
0–5	*Indigofera zollingeriana*	213ab	209a	422ab	272a	513ab	242a	755ab	32a
0–5	Natural fallow	257a	230a	488a	297a	587a	269a	856a	32a
0–5	Maize/bean rotation	183ab	196a	378ab	279a	493ab	227a	720ab	31a
0–5	*Tithonia diversfolia*	151b	182a	333b	262a	436b	209a	645b	32a
5–10	*Calliandra houstoniana*	168a	166a	334a	249ab	439ab	191a	630a	30b
5–10	*Indigofera zollingeriana*	206a	204a	409a	257ab	484ab	232a	716a	33ab
5–10	Natural fallow	130a	230a	360a	228b	381b	259a	640a	39a
5–10	Maize/bean rotation	186a	204a	390a	240ab	449ab	234a	683a	34ab
5–10	*Tithonia diversifolia*	218a	210a	428a	282a	531a	241a	772a	31b
10–20	*Calliandra houstoniana*	157a	176a	333a	233a	409a	201a	610a	32a
10–20	*Indigofera zollingeriana*	174a	186a	360a	257a	447a	209a	656a	32a
10–20	Natural fallow	132a	151a	283a	220a	368a	172a	540a	32a
10–20	Maize/bean rotation	142a	157a	298a	222a	381a	180a	561a	32a
10–20	*Tithonia diversifolia*	146a	141a	287a	243a	406a	163a	570a	29a
Experiment BM2									
0–5	*Calliandra houstoniana*	147a	158a	304a	199a	359a	175a	534a	33a
0–5	*Indigofera zollingeriana*	162a	168a	330a	199a	376a	186a	562a	33a
0–5	Natural fallow	188a	188a	376a	225a	431a	209a	640a	33a
5–10	*Calliandra houstoniana*	146a	162a	307a	203ab	361a	178a	538a	33a
5–10	*Indigofera zollingeriana*	145a	161a	305a	261a	417a	178a	595a	30a
5–10	*Natural fallow*	152a	167a	319a	191b	357a	184a	540a	34a
10–20	*Calliandra houstoniana*	100a	134a	234a	158a	265a	147a	412a	36a
10–20	*Indigofera zollingeriana*	97a	134a	231a	151a	255a	147a	402a	36a
10–20	Natural fallow	104a	158a	262a	162a	274a	172a	446a	39a

[#] For a given soil nitrogen parameter and depth, LS-means within a column followed by the same letter(s) are not statistically significantly different, using the BONFERRONI multiple comparison method based on probability values (*P*-values) at $\alpha = 0.05$; NaOH–Pi = sodium hydroxide extractable inorganic P; NaOH–Po = sodium hydroxide extractable organic P; NaOH–Pt = sodium hydroxide extractable total P; Residual P = stable P; Total Pi = total inorganic P; Total Po = total organic P; Total P (Pi + Po) = sum of organic and inorganic P

interest here is total Po because P in organic pools is better protected from losses due to fixation than P in inorganic pools in volcanic-ash soils with high P-sorbing capacity (Phiri et al. 2001). Phosphorus in organic pools interacts less with soil, thereby minimizing chances of loss and increasing P cycling. Lack of significant improvement of the organic P pool by the fallow treatments therefore suggests that significant differences observed by Phiri et al. (2001) were transient and there continues to be a high potential for P fixation in volcanic-ash soils of this agroecosystem.

Soil organic matter fractions

Three soil organic matter (SOM) fractions (LL, LM and LH) were recovered using size-density fractionation as described by Phiri et al. (2001), Barrios et al. (1996a) and Meijboom et al. (1995). These fractions have shown potential as more sensitive indicators of the impacts of change in land use or cropping management than total SOM content, especially for topsoil layers. According to Hassink (1994), total SOM content is less sensitive as an indicator of sustainability of land use systems, because it changes relatively slowly under different management regimes and has a high spatial variability.

In both experiments, significant results for the weights of the SOM fractions as affected by system treatments were obtained in most soil layers (Table 5). The weights decreased in the order LL > LM > LH. For experiment BM1, the average SOM fractions weights for the LL, LM and

Table 5 Influence of planted allows on the weights and the carbon,nitrogen and phosphorus contents of the soil organic matter fractions[#]

Soil depth (cm)	Fallow species or cropping system	LLW mg kg^{-1}	LMW	LHW	LLCS g kg^{-1}	LMCS	LHCS	LLNS mg kg^{-1}	LMNS	LHNS	LLPS	LMPS	LHPS
Experiment BM1													
0–5	*Calliandra houstoniana*	780a	450a	140a	363b	324b	234ab	18ab	18ab	12b	702ab	681b	821bc
0–5	*Indigofera zollingeriana*	350b	270b	80b	406a	374a	307a	19a	21a	16a	969a	953a	903b
0–5	Natural fallow	720a	230bc	50bc	393ab	371a	280a	10c	15b	13b	627b	740b	787bc
0–5	Maize/bean rotation	200c	170c	20c	387ab	345ab	163b	16ab	17b	6.5c	1,079a	1015a	634c
0–5	*Tithonia diversifolia*	330bc	410a	30bc	382ab	355ab	229ab	14b	17b	13b	793ab	1,006a	1,255a
5–10	*Calliandra houstoniana*	310b	320a	80a	379b	349a	213a	17a	17ab	11a	836bc	813b	919b
5–10	*Indigofera zollingeriana*	60c	90b	20b	422a	380a	216a	16a	19a	14a	1,053ab	910ab	1,057ab
5–10	Natural fallow	440a	80b	20b	382b	351a	287a	11b	14b	12a	686c	786b	997ab
5–10	Maize/bean rotation	150c	80b	20b	396ab	363a	260a	16a	16ab	13a	1,170a	1,073a	1,163a
5–10	*Tithonia diversifolia*	60c	80b	30ab	424a	379a	259a	16a	16ab	12a	967abc	1,006a	954ab
10–20	*Calliandra houstoniana*	280a	170a	30a	395a	339b	270a	16a	15ab	11a	753abc	864a	844ab
10–20	*Indigofera zollingeriana*	120b	80a	40a	423a	394a	185a	15ab	18a	11a	1,035a	942a	797b
10–20	Natural fallow	330a	110a	50a	412a	372ab	188a	10c	13b	8.0b	640c	890a	884ab
10–20	Maize/bean rotation	90b	80a	30a	406a	361ab	249a	15ab	15ab	10ab	1,026ab	959a	959ab
10–20	*Tithonia diversifolia*	90b	80a	20a	417a	378a	218a	12bc	13b	10ab	737bc	904a	1,036a
Experiment BM2													
0–5	*Calliandra houstoniana*	2,380a	600a	30a	389a	358a	284a	17a	16b	13a	599c	671b	783a
0–5	*Indigofera zollingeriana*	500b	340b	30a	390a	348a	228a	18a	18a	12a	947a	951a	889a
0–5	Natural fallow	600b	580ab	30a	376a	344a	241a	13b	14b	11a	782b	853a	954a
5–10	*Calliandra houstoniana*	1,230a	450a	50a	398a	348a	231a	17a	14ab	11a	657a	695b	716a
5–10	*Indigofera zollingeriana*	510b	240ab	40a	389a	335a	177a	16a	16a	11a	746a	868a	842a
5–10	Natural fallow	520b	210b	60a	377a	340a	246a	12b	13b	11a	667a	846a	921a
10–20	*Calliandra houstoniana*	630a	240b	110a	399a	345a	243a	14a	14a	11a	513a	630a	665a
10–20	*Indigofera zollingeriana*	270b	580a	120a	393a	336a	128b	12a	13ab	8.9a	611a	670a	700a
10–20	Natural fallow	320ab	300b	140a	355b	317a	223ab	10b	11b	8.6a	617a	672a	687a

[#] For a given soil nitrogen parameter and depth, LS-means within a column followed by the same letter (s) are not statistically significantly different, using the BONFERRONI multiple comparison method based on probability values (*P*-values) at $\alpha = 0.05$; LLW = weight of the Ludox light fraction; LMW = weight of the Ludox intermediate fraction; LHW = weight of the Ludox heavy fraction; LLCS = carbon content in the Ludox light fraction; LMCS = carbon content in the Ludox intermediate fraction; LHCS = carbon content in the Ludox heavy fraction; LLNS = nitrogen content in the Ludox light fraction; LMNS = nitrogen content in the Ludox intermediate fraction; LHNS = nitrogen content in the Ludox heavy fraction; LLPS = phosphorus content in the Ludox light fraction; LMPS = phosphorus content in the Ludox intermediate fraction; LHPS =phosphorus content in the Ludox heavy fraction

LH at the 0–5 cm soil depth accounted for 11.3, 7.3 and 1.4% of the sum of all the SOM fractions, respectively. For experiment BM2, they accounted for 22.7, 10 and 0.6%, respectively. The recovery of SOM size-density fractions is far lower than that obtained by Phiri et al. (2001) in the same experiment, one year after establishment of the fallow experiment. This could be explained by the fact that most SOM in this tropical environment could have been oxidized during the dry season prior to sampling of the soils. Increased soil temperatures can significantly reduce SOM fraction quantity as observed by Tiessen and Stewart (1983).

Barrios and Cobo (2004) have reported significantly higher leaf biomass for CAL and IND at both experimental sites BM1 and BM2, though biomass from other plant parts as well as nutrient accumulation were similar at both sites. This finding has important implications for long-term site productivity as CAL biomass may lead to a better synchronization of nutrient release and crop demand. Therefore, for sustainable agricultural productivity, CAL may be a better candidate than the faster decomposing (high quality biomass) TTH or IND.

Natural fallow produced significantly higher weights of the LL fraction in all soil layers in experiment BM1. A mixture of local plant communities could probably have led to higher SOM in the NAT fallow treatment. This finding seems to complement results by Meijboom et al. (1995) who recovered highest weights of the LL SOM fraction on natural grassland soils. For experiment BM2, significantly higher weights of the LL SOM fraction for all soil layers were found in CAL. Furthermore, CAL produced significant results for the weights of the LM and LH SOM fractions in most soil layers in both experiments. This confirms results by Cobo et al. (2002a) and Barrios et al. (2004) who have reported Calliandra as a fallow species that produces large quantities of low quality biomass. It has been consistently found that the amount of the light fraction is affected by the amount of litter production and its quality (Christensen 1992).

In experiment BM1, the impact of fallow systems on the contents of C, N and P in the SOM fractions clearly narrows down to IND showing significant results in the 0–5 cm soil layer (Table 5). On average, IND out-performed all the other fallow system treatments in the other soil layers, with NAT performing worst. The same trend of results is observed in experimental site BM2. These results contrast with those of Phiri et al. (2001) who reported that TTH gave significantly higher values for the contents of C, N and P in the SOM fractions of the 0–5 cm soil layer in the same experiment, one year after establishment of the fallows; and that CAL performed significantly better than the other fallow treatments in the 5–10 cm soil layer. These observations suggest that the impact of different fallow species can be inconsistent in some cases as fallow plants can have diverse responses to environmental conditions and system management. The use of mixed fallows may be a more effective strategy to maximize on the residual benefits in terms of nutrient contribution to the soils (Yamada and Gholz 2002).

Conclusions

In this study, we confirmed that mineral nitrogen, weight and nutrient content of SOM fractions and soil phosphorus fractions were sensitive to soil management using planted fallows on inherently variable volcanic-ash soils in the hillsides of the Colombian Andes. These methodologies using soil organic matter pools and phosphorus fractions have been an important alternative to conventional methods that determine total soil nutrient contents that do not distinguish active forms of the nutrients.

At the conclusion of this on-farm experiment, planted fallow systems studied were found to have generated slight improvements in soil N and P availability compared to the natural regeneration of native vegetation. This contrast with much higher differences found 12 months after planted fallow management in the same experiments and thus questions the need for 28-month fallow periods with species studied. However, other factors linked to the system such as economic attractiveness of planted fallows to farmers in addition to soil fertility recovery, like those associated with the production of firewood, would need to be also considered for future studies on trade-off analysis.

The choice of experimental on-farm sites with soils following two seasons (3 years) of cassava mono cropping at the end of the cropping cycle recognized the capacity of cassava to further deplete soil nutrients and the entry point for planted fallow systems for a more rapid regeneration of soil fertility than the natural fallow. Our results suggest that for effective regeneration of soil N and P availability in the volcanic-ash soils with high P-fixation, there is need for external nutrient inputs in addition to the planted fallow effect. Further studies should evaluate the soil nutrient replacement value provided by planted fallow systems and thus the reduction in amount of fertilizer expenditures by resource-limited farmers. In addition, multiple-location testing of best bet planted fallow species should be conducted to identify the biophysical and socioeconomic limits of the planted fallow technology in the Andean hillsides.

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