

Cover crops alter phosphorus soil fractions and organic matter accumulation in a Peruvian cacao agroforestry system

Hollie Hall · Yuncong Li · Nicholas Comerford ·
Enrique Arévalo Gardini · Luis Zuniga Cernades ·
Virupax Baligar · Hugh Popenoe

Received: 11 January 2010 / Accepted: 23 June 2010 / Published online: 6 July 2010
© US Government 2010

Abstract In many tropical soils, excessive weathering of primary minerals confounded by intense agricultural production has resulted in the depletion of organic matter and plant available forms of phosphorus (P). Long-term growth of cover crops in tropical agroforestry systems have been shown to influence nutrient cycling, and soil organic matter pools. The objective of this experiment was to assess the affect of 2 years of cover-crop cultivation on organic matter accumulation and P bioavailability using Mehlich I and sequential fractionation methods. The experiment included six treatments in the understory of a cacao-plantain agroforestry system adjacent to lower montane tropical forests of the San Martin district of Eastern Peru. Cacao and plantain

formed the primary canopy on otherwise abandoned agricultural land. The treatments consisted of four perennial leguminous cover crops (*Arachis pintoii*, *Calopogonium mucunoides*, *Canavalia ensiformis*, and *Centrosema macrocarpum*), a non-legume cover crop (*Callisia repens*), and a control treatment (no cover crop). After only 2 years of cultivation, results suggest that all cover crop species accessed residual P pools in 0–5 cm soil depths as indicated by a decrease in the 0.5 M HCl extractable P pools when compared to control. Additional use of residual P pools by *A. pintoii* and *C. macrocarpum* were indicated by significant reduction in the 6.0 M HCl extractable P pool. Relative to control, there was no treatment effect on soil organic matter content; however significant differences occurred between treatments. The *C. ensiformis*, *C. mucunoides* and *C. repens* treatments in 5–15 cm soil depths contained significantly more organic matter than the *A. pintoii* treatment. In 15–30 cm soil depths the *C. ensiformis* treatment contains significantly more organic matter than the *A. pintoii* treatment. Continued research should focus on monitoring the long-term effects of cover crop cultivation on the bioavailability of soil P pools in surface soil horizons, development of organic matter pools and the productivity of the agroforestry species.

H. Hall (✉) · Y. Li · N. Comerford · H. Popenoe
Soil and Water Sciences Department, University
of Florida, Gainesville, FL, USA
e-mail: HRHall@UFL.EDU

E. A. Gardini · L. Z. Cernades
Instituto de Cultivos Tropicales (ICT), Jr. Santa Maria
241, La Banda de Shilcayo, Tarapoto, San Martin, Peru

V. Baligar
The Agricultural Research Service, United States
Department of Agriculture, Washington, DC, USA

Keywords Leguminous plants · Mehlich I ·
Sequential fractionation · Tropical soil fertility

Introduction

A typical process for conversion of tropical forest to agricultural land involves the removal of primary forest and subsequent burning of organic matter on the forest floor. This process accelerates the rate of soil organic matter (SOM) cycling, nutrient mineralization and leaching, effectively reducing the capacity for nutrient storage that is mediated by organic pools (Davidson et al. 2007; Tiessen et al. 1994). Once converted from forest to agriculture, tropical soils tend to have structure suitable for plant growth but lack quantities of plant essential nutrients required for long-term agricultural productivity (Lindell et al. 2010).

Commonly, the productivity of continuously cultivated tropical soils is limited by insufficient supplies of soil minerals, particularly phosphorus (P) (Wood and Lass 2001). Depletion of soil P pools continues through sequential harvest and removal of animal or plant agricultural products (Cardoso et al. 2003; Hedley et al. 1982a, b). Application of inorganic P containing fertilizers to remedy the infertility of these soils is not an option for many subsistence farmers in developing countries without money to buy, or means to transport them (Appiah et al. 1997). It is possible that with better management, fertility of these soils can be maintained for a longer period, enhancing their capacity to sustain agricultural productivity (Lindell et al. 2010).

Leguminous cover crops are widely accepted for their contribution to soil quality through addition of organic carbon and nitrogen (N) in agricultural systems (Baligar and Fageria 2007; Fageria et al. 2005; Ghosh et al. 2007; Schroth et al. 2001). As P is often the most limited plant essential nutrient in tropical soils, inclusion of leguminous cover crops on tropical soils may seem counter-intuitive. However, leguminous cover crops may increase available P pools in surface soils by: mining P from deeper soils, conversion of previously occluded P to organic matter, and priming microbial mediated P cycling in the upper soil horizons through root exudation (Brady and Weil 1999; Chapin et al. 2002; Fageria and Stone 2006; Ghosh et al. 2007; Hinsinger 2001; Lambers et al. 2006; Li et al. 2007; Schactman et al. 1998).

The objective of this study was to determine the effects of leguminous cover crop cultivation in a cacao agroforestry system on soil P bioavailability.

Soil P was extracted using the Mehlich I procedure commonly utilized to measure the plant available P pool and a modified sequential fractionation of soil P procedure (Kuo 1996; Nair et al. 1995). The sequential fractionation of P allows the extraction of sequentially increasingly residual P pools. Fractionation of soil P pools aids in the development of an understanding for the fluctuation between sources and sinks of P in the soil system (Hinsinger 2001; Barber 1995; Nair et al. 1995; Tiessen and Moir 1993). Use of this method is particularly informative in determining whether or not cover crops mediate the cycling between residual and labile P pools. Deciphering the influences of cover crops on soil P pool cycling will aid in the development of management strategies for the alleviation of P limitations to agricultural productivity in tropical soils.

Materials and methods

Study site

The field experiment was conducted at the research farm of Instituto de Cultivos Tropicales (ICT) which lies at latitude 6°28.734' S and longitude: 76°19.694' W, with an elevation of 356 meters above sea level in Tarapoto, Peru. The site receives an average of 1200 mm of precipitation per year. The annual maximum temperature is 25.5°C and the annual minimum is 19°C (NOAA 2007). The landscape of the San Martin Region of Peru is best described as hillsides feathered by rivers and streams. The soils here are acidic loamy sand Inceptisols. Other than inclusion of cover crops, the agroforestry system management style is that of the traditional methods of local cacao farmers in the San Martin Region of Peru. These methods consist only of harvesting mature agroforestry products, in this case cacao and plantain.

Experimental design

To test the influence of leguminous cover cropping on soil fertility in an experimental cacao agroforestry system, a randomized block design was established on 1.05 hectares of abandoned agricultural land. Site preparation commenced in June 2004 with the clearing and burning of the fern *Pteridium* sp. dominated site. Subsequently cover crops, cacao, and bananas were

planted on the site. Four leguminous crops included in the experiment were *Arachis pintoi* (perennial peanut), *Calopogonium mucunoides* (calo), *Canavalia ensiformis* (jack bean), and *Centrosema macrocarpum* (macrocarpum). Additionally, one non-legume cover crop *Callisia repens* (inch plant), and one control treatment were included in the experiment. *Callisia repens* is a native forest ground cover in the region. The leguminous cover crops utilized are known to grow well in tropical climates. The control treatment was planted with cacao and plantain in the same density as the other treatments, however it lacked a formerly planted cover crop and weeds sparsely covered the soil surface. Each treatment was replicated three times, once in each of three randomized blocks, each block is 10 × 45 m with a 2 m buffer between each treatment. Each block contained one plot of each treatment, arranged in a random order.

Soil sampling

Soil samples were collected mid July–mid August in 2006. Ten soil samples were collected from the 0–5 cm, 5–15 cm, 0–15 cm and 15–30 cm soil depths of each replicate of each treatment using a 5 cm diameter stainless steel sampling tube. The ten soil samples corresponding by treatment, depth, and block were combined at the time of sampling to form one composite sample. This sampling scheme resulted in 72 composite samples collected from the entire cover crop management experiment. All collected soil samples were transported to the laboratory, labeled, and air-dried. Each soil sample was mixed by hand, air-dried, and passed through a 2 mm sieve prior to soil chemical analysis (Basamba et al. 2006; Graetz and Nair 1999; Phiri et al. 2001).

Phosphorus extraction

Mehlich I extractions of P were conducted on air-dried soil from the 0–15 cm depth following established methods (Kuo 1996). To calculate the organic P (Po) portion of P in the Mehlich I extraction, the supernatant was digested at 340°C in concentrated sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂), and Po was determined by subtraction of the P concentration in the undigested from the digested sample.

Sequential fractionation of P was modified from the procedure detailed in Nair et al. (1995) with the addition of an initial deionized H₂O extraction and the quantification of Total P on un-extracted, air-dried soil (Nair et al. 1995). Total P of air-dried soil was determined by ashing 1.0 g of air-dried soil for 2 h and then solubilizing with 6 M HC (Nair et al. 1995). A schematic of the utilized extraction procedure is depicted in Fig. 1.

Measurement of extracted inorganic phosphorus

Concentrations of extracted inorganic P contained within extract solutions were measured using the Murphy and Riley method (Kuo 1996). Strongly alkaline or acidic extract solutions were neutralized prior to analysis.

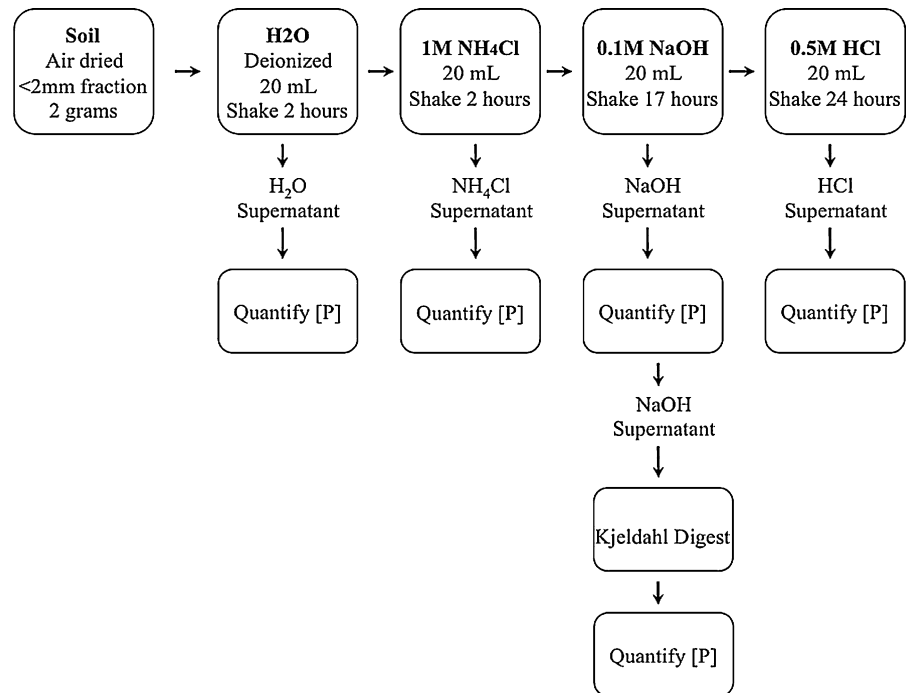
Analysis of soil organic matter

Although Loss on Ignition (LOI) tends to slightly over estimate the organic matter proportion of a soil due to the ignition of a fraction of inorganic materials at high temperatures, it is often utilized to estimate soil organic matter content (Heiri et al. 2001; Nelson and Sommers 1996). To estimate soil organic matter content LOI was determined for all treatments and soil depths using methods published by the Soil Science Society of America (SSSA) and the American Society of Agronomy (ASA) (Nelson and Sommers 1996).

Statistical analysis

Determinations of insignificant blocking affects and significant treatment and depth affects were tested by analysis of variance (ANOVA) and post hoc comparisons using JMP® 5.1 statistical software. When necessary, data transformations to meet the parametric statistical assumptions of normality and equal variances were conducted using Box and Cox Transformations. Initial significance tests between the pooled data of all treatments and depths was determined to assess variation between depths, followed by an ANOVA between treatments at each depth to assess variation between treatments within each depth. When the *F* values were significant, post hoc comparisons of means were made using Dunnett's Method and Tukey-Kramers HSD. Dunnett's Method was utilized to

Fig. 1 Sequence for the fractionation of soil phosphorus pools. Adapted from Nair et al. (1995)



determine significant differences in variance between the data of any treatment and that of the control. Tukey-Kramers HSD was utilized to determine significant differences in variance between the data of any treatment and that of any other treatment.

Results

Extractable phosphorus

Mehlich I extractable P pools were not significantly influenced after 2 years of cover crop cultivation. With regard to the sequential extraction of P: no significant differences were found between the control and any treatment for the H₂O, NH₄Cl, NaOH[P] or NaOH[TP] extractable P pools. See Table 1 for Mehlich I extraction of inorganic, organic, and total phosphorus averaged data. However, treatment effects did occur in the HCl extractable P pools. For the 0.5 M HCl pool in the 0–5 cm soil depth a significant decrease in all treatments relative to control occurred as follows: *A. pintoi* 11.52 mg kg⁻¹ less, *C. ensiformis* 22.57 mg kg⁻¹ less, *C. macrocarpum* 8.48 mg kg⁻¹ less, *C. mucunoides* 21.39 mg kg⁻¹ less and *C. repens* 21.36 mg kg⁻¹ less (Table 2). Significant differences

also occurred in the 6.0 M HCl pools in the 5–15 cm soil depth. The *C. ensiformis* treatment contained significantly more P than *A. pintoi* or *C. macrocarpum* (67.53 mg kg⁻¹ and 65.02 mg kg⁻¹ more respectively) (Table 2). Analysis of the pooled data to allow for comparisons between soil depths showed the 0–5 cm soil depth to contain significantly greater concentrations of H₂O, NH₄Cl and NaOH extractable phosphorus than the underlying depths. See Table 3 for soil pH and P fraction data by soil depth.

Soil organic matter

The cover crop treatments varied in effects on soil organic matter content. While there was no significant treatment effect when compared to the control there were significant differences between the treatments. In the 5–15 cm soil depth the *C. repens*, *C. mucunoides*, and *C. ensiformis* treatments all contained significantly more organic matter than did the *A. pintoi* treatment (5.18%, 5.17%, 4.84%, 1.44%, respectively; Table 2). Also, in the 15–30 cm soil depth the *C. ensiformis* treatment contained significantly more organic matter than did the *A. pintoi* treatment (4.93% vs. 2.79%; Table 2).

Table 1 Mehlich I extraction of inorganic, organic, and total phosphorus averaged data

Treatment	Depth (cm)	Inorganic [P] (mg kg ⁻¹)	Organic [P] (mg kg ⁻¹)	Total [P] (mg kg ⁻¹)	Inorganic P (%)	Organic P (%)
<i>A. pintoi</i>	0–15	2.03	6.31	8.34	24.35	75.65
<i>C. repens</i>	0–15	3.14	10.89	14.03	22.38	77.62
<i>C. mucunoides</i>	0–15	2.79	8.63	11.42	24.41	75.59
<i>C. ensiformis</i>	0–15	3.92	12.16	16.08	24.40	75.60
<i>C. macrocarpum</i>	0–15	2.54	7.86	10.39	24.40	75.60
Control	0–15	2.47	7.66	10.13	24.40	75.60
Fertilized	0–15	3.87	11.98	15.85	24.40	75.60

Table 2 Phosphorus fractions in soils collected from three depths under cover crops or control plots. Each value represents the average of 3 laboratory replicates

Treatment	Depth (cm)	LOI (%)	H ₂ O [P] (mg kg ⁻¹)	NH ₄ Cl [P] (mg kg ⁻¹)	NaOH [P] (mg kg ⁻¹)	NaOH [TP] (mg kg ⁻¹)	0.5 HCL [P] (mg kg ⁻¹)	6.0 M HCl [TP] (mg kg ⁻¹)
<i>A. pintoi</i>	0–5	5.04	0.84	0.09	18.66	29.24	21.38a	213.85
<i>C. ensiformis</i>	0–5	6.91	1.53	0.31	31.24	55.33	10.33a	278.07
<i>C. macrocarpum</i>	0–5	6.39	0.94	0.15	31.27	41.99	24.42a	239.20
<i>C. mucunoides</i>	0–5	4.22	1.24	0.01	41.53	29.26	11.51a	193.58
<i>C. repens</i>	0–5	2.49	1.25	0.17	36.08	42.79	11.54a	288.85
Control	0–5	4.06	0.82	0.14	34.05	39.28	32.90b	177.49
<i>A. pintoi</i>	5–15	1.44a	0.54	0.01	20.02	32.18	33.32	188.13a ^a
<i>C. ensiformis</i>	5–15	4.84b	0.59	0.04	25.93	34.66	16.50	255.66b
<i>C. macrocarpum</i>	5–15	1.71	0.64	0.15	28.99	27.98	16.50	190.64a
<i>C. mucunoides</i>	5–15	5.17b	0.40	0.02	17.84	28.40	24.85	204.41
<i>C. repens</i>	5–15	5.18b	0.52	0.05	39.17	44.39	28.89	247.74
Control	5–15	3.51	0.42	0.09	25.01	30.07	24.55	202.49
<i>A. pintoi</i>	15–30	2.79b	0.70	0.04	17.87	29.76	28.32	197.57
<i>C. ensiformis</i>	15–30	4.93a	0.88	0.12	19.82	37.54	18.02	245.59
<i>C. macrocarpum</i>	15–30	3.78	0.70	0.11	23.43	32.36	20.87	207.94
<i>C. mucunoides</i>	15–30	4.26	0.69	0.01	20.76	28.24	15.42	208.09
<i>C. repens</i>	15–30	3.66	0.76	0.22	29.53	36.40	19.23	270.23
Control	15–30	3.65	0.59	0.08	27.50	33.76	23.76	196.48

^a Mean values followed by different letters within same column and same soil depth indicate significant differences at the $P < 0.05$ level. When the F values were significant, post hoc comparisons of means were made using Dunnett's Method and Tukey-Kramers HSD. Dunnett's Method was utilized to determine significant differences in variance between the data of any treatment and that of the control. Tukey-Kramers HSD was utilized to determine significant differences in variance between the data of any treatment and that of any other treatment

Discussion

Extractable phosphorus

Cultivation of cover crops had a significant effect in the HCl extractable P pools in the 0–5 and 5–15 cm soil depths. At the 0–5 cm soil depth, the five cover crop treatments averaged 16.82 mg kg⁻¹ less 0.5 M

HCl extractable P than the control. At the 5–15 cm depth, *A. pintoi* and *C. macrocarpum* treatments contained significantly less extractable P in the 6.0 M HCL extractable P pool than the *C. ensiformis* treatment (67.53 mg kg⁻¹ and 65.02 mg kg⁻¹ less, respectively). Assuming that the soil of the entire agroforestry system contained near uniform concentrations of P prior to the experiment, it is likely that

Table 3 Phosphorus fractions and pH for soils collected from three depths. Each value represents the mean of pooled data for all treatments

Depth (cm)	pH	H ₂ O [P] (mg kg ⁻¹)	NH ₄ Cl [P] (mg kg ⁻¹)	NaOH [P] (mg kg ⁻¹)	NaOH [TP] (mg kg ⁻¹)	0.5 HCL [P] (mg kg ⁻¹)	6 M HCl [P] (mg kg ⁻¹)
0–5	5.41a	0.12a	0.21a	34.86	43.44a	19.19	237.63
5–15	5.13b	0.05b	0.07b	29.21	35.61b	23.61	222.02
15–30	5.03b	0.05b	0.08b	23.60	26.02b	20.61	217.87

^a Mean values followed by different letters within same column indicate significant differences at the $P < 0.05$ level

the reductions in HCl extractable P pools are a result of P uptake by the cover crops. This finding is significant since the HCl extractable P pools are typically thought to originate from primary minerals, calcium-P compounds, or sesquioxides (Crews 1996; Hedley et al. 1982a; Hielajes and Lijklema 1980; Hinsinger 2001; Kurmies 1972). The soil of this experiment contains negligible concentrations of calcium (unpublished data) and the primary minerals have long ago weathered (Clark and Baligar 2000). The only explanation remaining is that the cover crops have used phosphate that is occluded within the weathered iron and aluminum oxides of the soil. This pool of P is strongly bound to iron and aluminum and is commonly referred to as the ‘residual’, ‘fixed’ or ‘occluded’ P pool to indicate that it is not readily available for plant uptake (Hedley et al. 1982a; Phiri et al. 2001; Zhang 2000). However, the results of several bodies of research indicate that acids released during organic matter decomposition and in the form of root or fungal exudates participate in ligand exchange reactions with sesquioxides releasing phosphate molecules into soil solution where they can be used by plants (Barroso and Nahas 2005; Clark and Baligar 2000; Crews 1996; Lambers et al. 2006; Schactman et al. 1998; Zhou et al. 2009). The overstory plantain and cacao are growing uniformly across the experiment, thus it is likely that if these plants were taking up the residual P, their uptake of P would be uniform across the experiment as well. Fortunately researchers at ICT are collecting productivity data from plantain and cacao to broaden the scope of this analysis.

The processes leading to a significant increase of extractable P in the *C. ensiformis* treatment could be caused by P transport or mobilization from deeper soils via roots and arbuscular mycorrhizae (Barroso and Nahas 2005; George et al. 2006; Jobbagy and Jackson 2004) but actual mechanisms remain

unknown. Perhaps though, defining the processes behind these changes are less important than the implications of this increase on the availability of P to future crops. Publications stemming from ongoing monitoring of this system will aid understanding of the alterations of soil P pools in this agroforestry system.

Soil organic matter

Cover crop cultivation effects on soil organic matter pools varied. In the 5–15 soil depth the *A. pintoi* and *C. macrocarpum* contained less combustible materials than the control (2.07% and 1.8% less than the control respectively). Whereas in the same depth *C. ensiformis*, *C. mucunoides* and *C. repens* contributed more organic matter to the soil than the control (1.33%, 1.66% and 1.97% more respectively). When analyzing the upper 0–30 cm soil depth, the *A. pintoi* cover crop contained 38,700 kg ha⁻¹ less soil organic matter than did the control. In this same depth the *C. ensiformis* contained 57,600 kg ha⁻¹ more soil organic matter than did the control. These differences in the amount of ignitable materials (e.g. organic matter) indicate that the rooting systems of *A. pintoi* and *C. macrocarpum* have a slow turn over rate, and are now storing organic materials. On the contrary, the rooting systems of *C. mucunoides*, *C. ensiformis*, and *C. repens* have stimulated the LOI pool, likely through a more rapid decomposition rate of their fine roots. The differences in the loss on ignition pools between treatments and the control indicate that cover crop cultivation has influenced soil organic matter pools. Increasing the soil organic matter content at this site is important for improving cacao production in the area, as the benefits of abundant supplies of organic matter include increased nutrient availability, and a reduction in the soils phosphorus fixation capacity (Sato and Comerford

2008; Young 1997). It is likely that the long-term crop productivity and soil fertility of the system under investigation would greatly benefit from increased soil organic matter supplies.

Conclusion

Improvement and maintenance of soil fertility will provide the foundation for sustained agricultural productivity in tropical soils. Alternatives to commercialized agrochemicals for building soil fertility have the potential to improve the livelihoods of small-scale farmers and reduce negative environmental impacts associated with fertilizer and topsoil runoff. Cover crops might provide an affordable and environmentally benign alternative to chemical fertilizers and slash and burn agricultural methods. However, prior to widespread promotion it is necessary to test alternative technologies extensively so that risk to livelihoods affected by technology adoption is minimized. This research tested the ability of cover crops to remediate the P fertility of an acidic loamy sand Inceptisol soil used predominantly for cacao cultivation. We found that the effects of cover crop cultivation are species dependent. After just 2 years of cultivation the P pools in the surface soils at this site were significantly altered, suggesting the importance of cover crop cultivation in the acceleration of P cycling through the uptake of less available (e.g. residual) P pools. However, quantification of the fluctuations across fractionated soil and plant P pools requires continued monitoring that includes all species in the agroforestry system to completely understand the effects of cover crop cultivation on P bioavailability over time.

Building and maintaining high contents of organic matter in surface soils are important for crop production and minimizing soil erosion. However, the cover crops included in this experiment vary in their rates of organic matter deposition. The *Arachis pintoi* and *Centrosema macrocarpum* treatments appear to not contribute organic matter after 2 years as compared to the *Cannavalia ensiformis*, *Calopogonium mucunoides*, and *Callisia repens* crops. The influence of cover crop cultivation on soil organic matter content should continue to be monitored to establish a clear trend of their cumulative affect on soil organic matter accumulation in the

longer term, as it is likely that soil organic matter additions will enhance soil fertility.

The cacao agroforestry site managed by ICT provides an ideal setting for examining the affects of cover crop cultivation on soil fertility. In this region, the soil fertility is hindered by soil acidity, high levels of aluminum, and low organic matter content. Additionally, if the potential for cover crop cultivation to partially ameliorate tropical soil infertility is demonstrated, a great potential for cover crop remediation of abandoned agricultural land in the area exists. The result could be conversion of more abandoned agricultural lands to a source of much needed food and economic products to the people of this region. While all of the cover crops included in the experiment at ICT are significantly altering the soil fertility the effects of 2 years of cover crop cultivation on P availability are not sufficient for promotion of cover crop cultivation beyond the research area at this time. Continued monitoring of the soil organic matter and P pools as well as the productivity of the other agroforestry species (cacao and plantain) is needed to identify the best cover crops for ameliorating soil fertility issues in this region.

Acknowledgements The authors would like to thank the many sources of assistance that made this work possible. In terms of laboratory and field assistance, the authors would like to acknowledge the many people at the Forest Soils Laboratory, Tropical Research & Education Centers Soil and Water Sciences Laboratory, and at the Instituto de Cultivos for the generosity of their time. Specifically, at the Forest Soils Laboratory the authors thank Aja Stoppe. At the Tropical Research & Education Centers Soil and Water Sciences Laboratory, the authors thank Guingin Yu, Yun Qian, and Laura Rosado. At the Instituto de Cultivos Tropicales, the authors thank the all of their employees. In terms of funding, the authors would like to thank the Latin American Studies Research Grant fund, and the Tinker Grant fund at the University of Florida.

References

- Appiah MR, Sackey ST, Ofori-Frimpong K, Afrifa AA (1997) The consequences of cacao production on soil fertility in Ghana: a review. *Ghana Journal of Agricultural Science* 30:183–190
- Baligar VC, Fageria NK (2007) Agronomy and physiology of tropical cover crops. *Journal of Plant Nutrition* 30:1287–1339. doi:10.1080/01904160701554997
- Barber SA (1995) Nutrient absorption by plant roots. In: Barber SA (ed) *Soil nutrient bioavailability: a mechanistic approach*. Wiley, New York, pp 49–84

- Barroso CB, Nahas E (2005) The status of soil phosphate fractions and the ability of fungi to dissolve hardly soluble phosphates. *Appl Soil Ecol* 46. doi:[10.1016/j.apsoil.2004.09.005](https://doi.org/10.1016/j.apsoil.2004.09.005)
- Basamba TA, Barrios E, Amezquita E, Rao IM, Singh BR (2006) Tillage effects on maize yield in a Colombian Savanna oxisol: soil organic matter and P fractions. *Soil Tillage Res* 91:131–142. doi:[10.1016/j.still.2005.11.010](https://doi.org/10.1016/j.still.2005.11.010)
- Brady NC, Weil RR (1999) The nature and properties of soils. Prentice-Hall, Inc., New Jersey, 881 pp
- Cardoso IM, Janssen BH, Oenema O, Kuyper TW (2003) Phosphorus pools in Oxisols under shaded and unshaded coffee systems on farmers' fields in Brazil. *Agroforest Syst* 58:55–64
- Chapin FS, Matson PA, Mooney HA (2002) Principles of terrestrial ecosystem ecology. Springer, New York, NY
- Clark RB, Baligar VC (2000) Acidic and alkaline soil constraints on plant mineral nutrition. In: Wilkinson RE (ed) Plant-environment interactions. Marcel Dekker, Inc., New York
- Crews TE (1996) The supply of phosphorus from native, inorganic phosphorus pools in continuously cultivated Mexican agroecosystems. *Agriculture, Ecosystems and Environment* 57:197–208
- Davidson EA, Carvalho CJR, Figueira AM, Ishida FY, Ometto JPHB, Nardoto GB, Saba RT, Hayashi SN, Leal EC, Vieira ICG, Martinelli LA (2007) Recuperation of nitrogen cycling in Amazonian forests following agricultural abandonment. *Nature* 447:995–998. doi:[10.1038/nature05900](https://doi.org/10.1038/nature05900)
- Fageria NK, Stone LF (2006) Physical, chemical, and biological changes in the rhizosphere and nutrient availability. *Journal of Plant Nutrition* 29:1–30
- Fageria NK, Baligar VC, Bailey BA (2005) Role of cover crops in improving soil and row crop productivity. *Commun Soil Sci Plant Anal* 36:2733–2757
- George TS, Turner BL, Gregory PJ, Cade-Menun BJ, Richardson AE (2006) Depletion of organic phosphorus from Oxisols in relation to phosphatase in the rhizosphere. *Eur J Soil Sci* 57:47–57. doi:[10.1111/j.1365-2389.2006.00767.x](https://doi.org/10.1111/j.1365-2389.2006.00767.x)
- Ghosh PK, Bandyopadhyay KK, Wanjari RH, Manna MC, Misra AK, Mohanty M, Subba Rao A (2007) Legume effect for enhancing productivity and nutrient use-efficiency in major cropping systems—an Indian perspective: a review. *J Sustain Agric* 30:59–86. doi:[10.1300/Jo64v30n01_07](https://doi.org/10.1300/Jo64v30n01_07)
- Graetz DA, Nair VD (1999) Inorganic forms of phosphorus in soils and sediments. In: Reddy KR, O'Connor GA, Schelske CL (eds) Phosphorus biogeochemistry in subtropical ecosystems. Lewis Publishers, Gainesville, pp 171–186
- Hedley MJ, Stewart JWB, Chauman BS (1982a) Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Sci Soc Am J* 46:970–976
- Hedley MJ, White RE, Nye PH (1982b) Plant-induced changes in the rhizosphere of rape (*Brassica napus* var. Emerald) seedlings. III. Changes in *L* value, soil phosphate fractions and phosphatase activity. *The New Phytologist* 91:45–56
- Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J Paleolimnol* 25:101–110
- Hieltjes AHM, Lijklema L (1980) Fractionation of inorganic phosphates in calcareous sediments. *Journal of Environmental Quality* 9:405–407
- Hinsinger P (2001) Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. *Plant Soil* 237:173–195
- Jobbagy EG, Jackson RB (2004) The uplift of soil nutrients by plants: biogeochemical consequences across scales. *Ecology* 85:2380–2389
- Kuo S (1996) Phosphorus. In: Sparks DL (ed) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America and American Society of Agronomy, Madison, pp 869–919
- Kurmies VB (1972) Zur Fraktionierung der Bodenphosphate. *Phosphorsäure* 29:118–151
- Lambers H, Shane MW, Cramer MD, Rearse SJ, Veneklaas EJ (2006) Root structure and functioning for efficient acquisition of phosphorus: matching morphological and physiological traits. *Ann Bot* 98:693–713. doi:[10.1093/aob/mcl114](https://doi.org/10.1093/aob/mcl114)
- Li L, Li S-M, Sun J-H, Zhou L-L, Bao X-G, Zhang H-G, Zhang F-S (2007) Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. *PNAS* 104:11192–11196
- Lindell L, Astrom M, Oberg T (2010) Land-use versus natural controls on soil fertility in the Subanean Amazon, Peru. *Sci Total Environ* 408:965–975. doi:[10.1016/j.scitotenv.2009.10.039](https://doi.org/10.1016/j.scitotenv.2009.10.039)
- Nair VD, Graetz DA, Portier KM (1995) Forms of phosphorus in soil profiles from dairies of South Florida. *Soil Sci Soc Am J* 59:1244–1249
- Nelson DW, Sommers LE (1996) Walkley-Black method. In: Bartels JM (ed) Methods of soil analysis. Part 3. Chemical methods. SSSA Book Series no. 5. Soil Science Society of America and American Society of Agronomy, Madison, pp 995–996
- NOAA (2007) Climate and daylight chart for Tarapoto, Peru. <http://ClimateCharts.com>
- Phiri S, Barrios E, Rao IM, Singh BR (2001) Changes in soil organic matter and phosphorus fractions under planted fallow and a crop rotation system on a Colombian volcanic-ash soil. *Plant Soil* 231:211–223
- Sato S, Comerford NB (2008) The non-recoverable phosphorus following sorption onto a Brazilian Ultisol. *Biol Fertil Soils* 44:649–652
- Schactman DP, Reid RJ, Ayling SM (1998) Phosphorus uptake by plants: from soil to cell. *Plant Physiol* 116:447–453
- Schroth G, Lehmann J, Rodrigues MRL, Barros E, Macedo JLV (2001) Plant-soil interactions in multistrata agroforestry in the humid tropics. *Agrofor Syst* 53:85–102
- Tiessen H, Moir JO (1993) Characterization of available P by sequential extraction. In: Carter MR (ed) Soil sampling and methods of analysis. Lewis Publishers, CRC Press, Boca Raton, pp 75–86
- Tiessen H, Cuevas E, Chacon P (1994) The role of soil organic matter in sustaining soil fertility. *Nature* 371:783–785
- Wood GAR, Lass RA (2001) Cocoa. Blackwell Science, Great Britain

- Young A (1997) Soil organic matter and physical properties. In: Agroforestry for soil management. CABI Publishing, New York, pp 98–110
- Zhang H (2000) Phosphorus fractionation. In: Pierzynski (ed) Methods of phosphorus analysis for soils, sediments, residuals, and waters. North Carolina State University, Raleigh, pp 50–59
- Zhou LL, Cao J, Zhang FS, Li L (2009) Rhizosphere acidification of faba bean, soybean and maize. *Sci Total Environ* 407:4356–4362