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Soil Phosphorus Dynamics, Acquisition and Cycling in Crop–Pasture–Fallow Systems in Low Fertility Tropical Soils: a Review from Latin America

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Abstract

Knowledge of the phosphorus (P) dynamics in the soil–plant system, and especially of the short- and long-term fate of P fertiliser in relation to different management practices, is essential for the sustainable management of tropical agroecosystems. A series of field trials was conducted in the tropical savannas and Andean hillsides in Colombia to follow the dynamics of P under different management systems. In tropical savannas in the Llanos of Colombia, in cereal–legume rotations (maize–soybean or rice–cowpea) and ley pasture systems, measurements of soil P fractions indicated that applied P moves preferentially into labile inorganic P pools, and then only slowly via biomass production and microbes into organic P pools under both introduced pastures and crop rotations. Field studies conducted to quantify the residual effectiveness of P fertiliser inputs in crop rotations in terms of both crop growth response and labile P pool sizes, indicated that soluble P applications to oxisols of Colombia remain available for periods that are much longer than expected for 'high P-fixing' soils, such as the oxisols of Brazilian Cerrados. In Andean hillsides of Colombia, the impact of short-term planted fallows to restore soil fertility in N and P-deficient soils by enhancing nutrient recycling through the provision of organic matter, was investigated. Results indicated that the fractionation of soil organic matter and soil P could be more effective for detecting the impact of planted fallows on improving soil fertility than the conventional soil analysis methods. Litterbag field studies contributed to characterisation of the rate of decomposition and nutrient release from green manures and organic materials that could serve as biofertilisers. The data sets from these field and greenhouse studies are valuable for further testing and validation of APSIM.

Phosphorus (P) deficiency is a widespread nutrient constraint to crop production on tropical and subtropical soils and it affects an area estimated at over 2×10^9 hectares (Fairhust et al. 1999). However, for most resource-poor farmers in developing countries, correcting soil P deficiency with large applications of P fertiliser is not a viable option. Furthermore, the inexpensive rock phosphate reserves remaining in the world could be depleted in as little as 60–80 years (Runge-Metzger 1995). Therefore, sustainable P management in agriculture requires additional information on the mechanisms in plants that enhance P

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acquisition in order to make plants more efficient at acquiring P, development of P efficient germplasm, and advanced crop management schemes that increase soil P availability (Rao et al. 1999a; Vance 2001).

Knowledge of the P dynamics in the soil–plant system, and especially of the short and long-term fate of P fertiliser in relation to different management practices, is essential for the sustainable management of tropical agro-ecosystems. Sequential chemical extraction procedures have been and still are widely used to divide extractable soil P into different inorganic and organic fractions (Hedley et al. 1982). The underlying assumption in these approaches is that readily available soil P is removed first with mild extractants, while less available or plant-unavailable P can be extracted only with stronger acids and alkali.

Several studies have related these different P fractions in tropical soils to plant growth (Crews 1996; Friesen et al. 1997; Guo and Yost 1998; Oberson et al. 1999, 2001; Phiri et al. 2001a, b; Lehmann et al. 2001; Bühler et al. 2002). The results obtained in these studies suggest that, in tropical soils, the amounts of P in the different pools measured by sequential P extraction procedures, and the fluxes of P between pools, are controlled both by physico-chemical factors such as sorption and desorption and by biological reactions such as immobilisation and mineralisation. However, the importance of these processes for different land-use systems, such as monocropping, pasture or intercropping, remains largely unknown.

CIAT researchers, in collaboration with their partners, conducted a series of field trials in the tropical savannas and Andean hillsides in Colombia. The main objectives of these studies were: (i) to quantify the soil and plant processes associated with changes in primary biomass productivity in typical systems and 'best bet' options to develop indicators of soil quality and degradation; (ii) to quantify and understand nutrient dynamics in systems to improve cycling and minimise losses; and (iii) to quantify factors that influence and determine the rates of processes to calibrate, modify, or develop simulation models for overcoming site specificity and testing alternative scenarios. We describe here the progress in quantifying soil P dynamics, acquisition and cycling under different management systems in tropical savannas and hillsides agro-ecosystems.

Tropical Savannas Agroecosystem — Llanos of Colombia

The neotropical savannas occupy 243 million hectares in South America and are one of the most rapidly expanding agricultural frontiers in the world (Thomas and Ayarza 1999), with oxisols predominating. Intensification of agricultural production in this ecosystem requires acid soil (aluminium) tolerant crop germplasm, soil fertility improvement and management of highly vulnerable physical properties (Amézquita 1998). Grain legumes, green manures, intercrops and leys are possible system components that could increase the stability of systems involving annual crops (Karlen et al. 1994). Soil P dynamics, acquisition and cycling were quantified in crop rotations and ley pasture systems (Friesen et al. 1997). Comparison of rooting patterns of crop and forage components indicated that introduced legume-based pastures are more deep-rooted than crops, and acquire considerable amounts of P despite a lower level of available P in the surface soil. Greenhouse studies indicated that forage legumes are more efficient in acquiring P per unit root length (Rao et al. 1997). Comparative studies of a forage grass (*Brachiaria dictyoneura* CIAT 6133) and a legume (*Arachis pintoi* CIAT 17434) demonstrated that the legume could acquire P from relatively less-available P forms from oxisols of Colombia (Rao et al. 1999b). Field studies on root distribution of maize showed that most of the roots are in top 20 cm of soil depth. These differences in rooting strategies have important implications for P acquisition efficiency in relation to available soil P in different crop and pasture systems (Table 1). Application of higher amounts of lime did not improve subsoil-rooting ability of maize but contributed to greater nutrient acquisition. This knowledge is useful to match the plant components to overcome edaphic constraints and to model plant responses to P supply in soil.

Observed differences in crop–forage residue decomposition and P release rates suggest that managing the interaction of these residues with soil could reduce P fixation. Measurements of soil P fractions indicated that applied P moves preferentially into labile inorganic P pools, and then only slowly via biomass production and microbes into organic P pools under both introduced pastures and crop rotations (Friesen et al. 1997). In cultivated soils, much higher P fertiliser doses significantly increase available inorganic P contents with lesser impact on organic P pool sizes. Agricultural land-use systems replacing native savanna on oxisols affect the partitioning of P among inorganic and organic P fractions (Table 2). The amount and turnover of P that is held in the soil microbial biomass is increased when native savanna is replaced by improved pasture while it was lowered when soils are cultivated and cropped continuously (Oberson et al. 2001). Based on these studies alternative strategies for cropping low P oxisols, involving strategic application of lower amounts of P fertiliser to crops and planting of grass–legume pastures, would promote P cycling and efficient use of P inputs.

Legume-based pastures (16 years old) maintained higher organic and available P levels than the grass alone or native pastures (Oberson et al. 2001). Greater turnover of roots and above-ground litter in legume-based pastures could provide for steadier organic inputs and therefore higher P cycling and availability. Failure of P to enter organic P pools is thought to indicate a degrading system due to low level of P cycling. If that is true, work done so far in the Llanos of Colombia indicates that legume-based pastures could be considered as important land-use options to stimulate P cycling, reduce P fixation and minimise soil degradation in tropical savannas.

Field studies were conducted to quantify the residual effectiveness of P fertiliser inputs in cereal–grain legume rotations (maize–soybean or rice–cowpea) in terms of both crop growth response and labile P pool sizes in an oxisol in the Llanos of Colombia (CIAT 1996; D. K. Friesen, unpublished data). The results showed that soluble P applications to oxisols of Colombia remain available for periods that are much longer than expected for 'high P-fixing' soils, such as the oxisols of Brazilian Cerrados. For determining the available P in low-P supplying oxisol, we compared an acid ammonium oxalate extraction method with Bray-II extraction, resin and bicarbonate extraction, and extraction with iron-impregnated paper strips (Guo and Yost 1998; CIAT 2001). This comparative study of P extraction methods indicated that use of either oxalate-P or resin-P + bicarbonate-P pools of Hedley sequential fractionation scheme are better suited to determine soil P availability in oxisols that receive strategic applications of lower amounts of fertiliser P.

Crop simulation models are increasingly used to estimate crop yields as affected by nutrients and water inputs as well as management practices and climatic conditions. A group of models, CERES for cereal simulation growth and CROPGRO for legume simulation, has been used successfully around the world for various purposes. A computer model for the simulation of P in soil and plant relations has been developed and added to the two above crop simulation models to enhance their capabilities, especially in tropical areas where P deficiencies are common. We tested these models using data on maize, soybeans and upland rice grown under acidic tropical conditions in the Colombian savannas (CIAT 2000; S. Daroub, unpublished data). The sensitivity analysis done on the model showed that it is responsive to different rates of P fertiliser applications as well as to initial conditions of labile P. Several growth parameters responded to P additions. Some of the growth parameters from the model that do not seem to be affected by P fertilisation are: flowering and maturity dates, panicle number and leaf number. This early work lead to the inclusion of P routines in DSSAT (Daroub et al. 2003).

Table 1. Differences among crop and pasture systems in accessible phosphorus (P) recovery in relation to available soil P (0–20 cm soil depth).

System	Bray-II available P (mg kg^{-1})	Total root length (km m^{-2})	Specific root length (m g^{-1})	Total P uptake (kg ha^{-1})	Accessible P recovery[a] (%)
Native savanna pasture	1.6	5.8	122	4	74
Introduced grass/legumes pasture[b]	3.5	7.2	75	14	94
Maize monoculture[c]	19.8	4.8	106	18	24

[a] Total P uptake per unit available P in rhizosphere soil (assuming an effective rhizosphere diameter of 5 mm).

[b] *Brachiaria humidicola* CIAT 679/*Stylosanthes capitata* CIAT 10280 + *Centrosema acutifolium* CIAT 5277 + *Arachis pintoi* CIAT 17434.

[c] *Zea mays* cv. Sikuani

Table 2. Distribution of phosphorus (P) in various fractions in fertilised land-use systems (continuous rice, grass–legume pasture) 5 years after establishment on native savanna as assessed from sequential extraction. Relative changes (% increase) describe the percentage of total P increase in fertilised systems over native savanna that was found in a given fraction (for formula see footnote †). Adapted from Oberson et al. (2001).

Treatment	Resin	$NaHCO_3$		NaOH		HCl		Resid	Sum		
	P_i	P_i	P_o	P_i	P_o	P_i	P_o	P_t	P_t‡	P_i§	P_o¶
Savanna											
Mean (mg kg^{-1})	2.6a	3.9a	11.3a	27.4a	45.3	35.6a	23.9	60.6	212a	69a	81.9
Grass–legume											
Mean (mg kg^{-1})	4.8b	6.7b	14.6b	45.5b	51.0	46.5b	30.3	62.2	263b	103b	97.8
% increase	4.3	5.4	6.5	35.5	11.3	21.4	12.6	3.2	101	66.6	31.1
Continuous rice											
Mean (mg kg^{-1})	14.3c	20.2c	17.1b	111.0c	42.7	54.3b	36.2	65.6	363c	200c	98.0
% increase	7.7	10.7	3.8	55.0	–1.7	12.3	8.1	3.3	100	85.8	10.6
F-test	***	***	**	***	ns	*	ns	ns	***	***	ns

Means of four field replicates samples per treatment. Means within a column followed by the same letter are not significantly different ($p = 0.05$) by Tukey's multiple range test. F-test: ***$p < 0.001$, **$p = 0.001$–0.01, *$p = 0.01$–0.05, ns = not significant.

† Increase (%) = (size of fraction in fertilised treatment – size of fraction in SAV) / (Sum P_t fertilised treatment – Sum P_t SAV) * 100

‡ Sum P_t = Resin P_i + $NaHCO_3$ P_t + NaOH P_t + HCl P_t + Resid P_t = Sum P_i + Sum P_o

§ Sum P_i = Resin P_i + $NaHCO_3$ P_i + NaOH P_i + HCl P_i

¶ Sum P_o = $NaHCO_3$ P_o + NaOH P_o + HCl P_o

A need identified during this simulation work was for a P rate and fractionation experiment in the Llanos designed specifically for testing P routines in simulation modelling. This four-year experiment, established in 2001, is a balanced P experiment, with a one-off addition of 80 and 160 kg P ha^{-1}, compared with annual applications of 5, 10, 20 and 40 kg P ha^{-1}. Crop yields from a maize–bean rotation and soil P fractionation will be used to further test the SoilP routine in APSIM and P routines in other simulation models. This work is ongoing and simulation modelling using APSIM will continue during 2004–2005.

The main lessons learned from the work in tropical savannas can be summarised as follows: 1) P from fertilisers and P released from organic residues flows preferentially into labile inorganic pools, but much more slowly into more stable pools; 2) P flows rapidly through, and does not accumulate in, organic pools in the short-term; and 3) crop and forage cultivars differ in their ability to acquire and utilise P, and these differences can be exploited to improve P input use efficiency in crop–livestock systems of the tropics.

Andean Hillsides Agroecosystem – Cauca, Colombia

Hillsides of tropical America cover about 96 million hectares (Jones 1993) and have important roles as reserves of biodiversity and source of water for areas downslope (Whitmore 1997). Agriculture in this region is often characterised by farming systems under which soils are degrading through erosion and loss of nutrients (Amézquita et al. 1998). Maintenance of the natural resource base in the hillsides is thus vital not only to ensure the future livelihood of resource-poor farmers, but also to prevent their migration to urban centres where social problems are already endemic. Agriculture in the Andean hillsides of Colombia is practised on steep slopes, on soils that are acidic, rich in allophane with a very high capacity to fix P, and prone to severe erosion, particularly on farms of the poorest farmers (Ashby 1985; Reining 1992).

Traditional agricultural systems in the Andean hillsides of Colombia are based on slash-and-burn shifting cultivation with 3–5 years of cropping and then abandonment to fallow vegetation because of low crop yields (Knapp et al. 1996). Local farmers recognise soil nutrient depletion and estimate that it takes more than 6 years for complete soil fertility recovery by natural fallows. Planted fallows are an appropriate technological entry point because of their low risk for the farmer, relatively low cost, and potential to generate additional products (i.e. fuelwood) that bring immediate benefit while improving soil fertility (Barrios et al. 2004).

The volcanic-ash soils in Colombian hillsides generally contain high amounts of soil organic matter (SOM) but nutrient cycling through SOM in these

Table 3. Decomposition and nutrient release differences among green manures and organic materials. Results are from a 20-week litterbag field study in hillsides of Cauca, Colombia. Adapted from Cobo et al. (2002b).

Plant species[a]	Decomposition rate (kD, d^{-1})	N release rate (kN, d^{-1})	P release rate (kP, d^{-})	Total N release (kg ha^{-1})	Total P release (kg ha^{-1})
CAN	0.019	0.045	0.033	116	8.0
CRA	0.009	0.026	0.015	90	3.5
IND	0.034	0.061	0.024	130	5.7
MDEE	0.019	0.048	0.044	144	11.4
MPBR	0.022	0.045	0.032	131	8.9
MPIT	0.020	0.039	0.029	110	7.7
MPTL	0.021	0.042	0.030	116	7.9
TTH	0.037	0.044	0.022	124	7.6
INDm	0.015	0.054	0.028	91	4.5
INDs	0.005	0.040	0.063	41	3.5
MPITm	0.017	0.028	0.032	83	6.5
MPITs	0.008	0.011	0.044	28	4.7

[a] CAN = *Canavalia brasiliensis* (leaves); CRA = *Cratylia argentea* (leaves); IND = *Indigofera constricta* (leaves); MDEE = *Mucuna deerengianum* (leaves); MPIT = *Mucuna puriens* var. IITA-Benin (leaves); MPTL = *M. puriens* var. Tanzania (leaves); MPBR = *M. puriens* var. Brunin (leaves); TTH = *Tithonia diversifolia* (leaves); INDm = *I. constricta* (stems + leaves); INDs = *I. constricta* (stems); MPITm = *M. puriens* var. IITA-Benin (stems + leaves); N = nitrogen; P = phosphorus.

soils is limited because most of it is chemically protected, which limits the rate of its decomposition (Phiri et al. 2001b). Short-term planted fallows on these P-fixing soils could restore soil fertility by enhancing nutrient recycling through the provision of organic matter to increase N supply and decrease P fixation (Barrios and Cobo 2004). Field and greenhouse studies were conducted to assess the magnitude and timing of nutrient release and to establish relationships with chemical characteristics (quality) of five green manures and four organic materials as a means of defining selection criteria for use as biofertilisers (Cobo et al. 2002a). Results indicated significant diversity in decomposition and nutrient-release patterns (Table 3) and highlighted the value of screening new farming system components to achieve efficient nutrient cycling and minimal environmental impact. Greenhouse studies on nitrogen mineralisation and crop uptake from surface-applied leaves of green manure species indicated that green manures that decomposed and released N slowly resulted in high N uptake when they were used at pre-sowing in a tropical volcanic-ash soil (Cobo et al. 2002b).

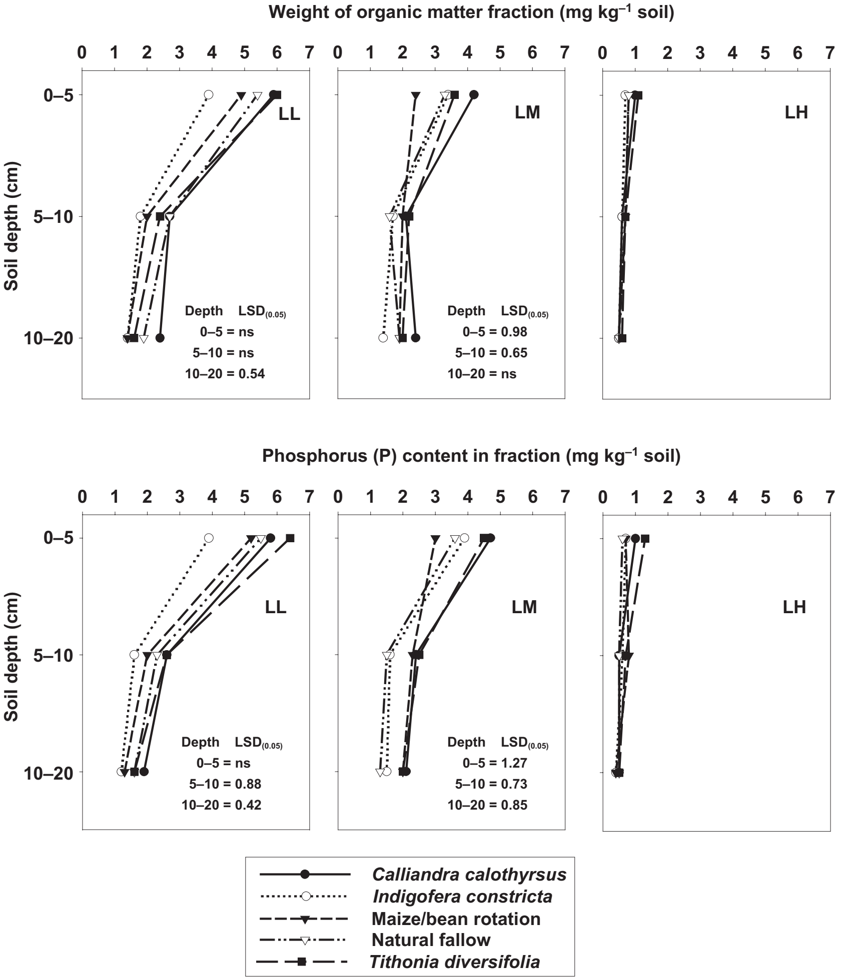

Figure 1. Soil profile weight distribution of light (LL), intermediate (LM), and heavy (LH) fractions of soil organic matter and their phosphorus (P) contents as affected by different fallows and the crop rotation system. LSD values are presented only when the differences among treatments are significant Adapted from Phiri et al. (2001b).

Studies on the impact of improved fallows on soil fertility indicated that a *Tithonia diversifolia* slash/mulch system has the greatest potential to improve soil fertility (Barrios et al. 2004; Barrios and Cobo 2004). Nevertheless, such a system may not be suitable for areas with seasonal drought as it is not very tolerant of extended dry periods. The *Calliandra calothyrsus* slash/mulch fallow system proved to be the most resilient as it produced similar amounts of biomass independent of initial level of soil fertility and was thus a candidate for wider testing as a potential source of nutrient additions to the soil and to generate fuelwood for resource-poor rural communities. The slower rates of decomposition in *C. calothyrsus*, compared with *Indigofera constricta* and T. *diversifolia,* indicated that the benefits provided may be longer lasting. The *I. constricta* slash/mulch fallow, on the other hand, was less adapted to low soil fertility and this may limit its potential for extended use.

The *T. diversifolia* slash/mulch fallow showed the greatest potential to improve SOM, nutrient availability, and P cycling, because of its ability to accumulate high amounts of biomass and nutrients (Phiri et al. 2001b; Barrios and Cobo 2004; Barrios et al. 2004). The amount of P in the light (LL) and medium (LM) fractions of SOM was greater with *T. diversifolia* fallow than the other two planted fallows (Figure 1) and it correlated well with the amount of 'readily available' P in the soil (Phiri et al. 2001b). It is suggested that the amount of P in the LL and LM fractions of SOM could serve as sensitive indicators of 'readily available' and 'readily mineralisable' soil-P pools, respectively, in P-fixing volcanic-ash soils. These results also indicated that fractionation of SOM and soil P could be more effective than the conventional soil analysis methods in detecting the impact of planted fallows on improving soil fertility.

The main lessons learned from the work in Andean hillsides can be summarised as follows: 1) the *Tithonia* slash/mulch fallow system appear to be the best option to contribute to the rapid restoration of soil fertility by increasing the plant available P pool in soil; and 2) a *Calliandra* fallow system could improve soil fertility and also provide good quality firewood for cooking for resource-poor farmers.

The Way Forward

Strategic P inputs are an essential component to increased and sustained agricultural production in low-P soils. Strategic P applications based on soil P availability, soil P fixation, crop P uptake and reduced crop P requirements could gradually increase the level of available P in the soil. Consequently, the frequency and amounts of P applications required to sustain production will decrease with time. Combined with strategic P inputs, P-efficient germplasm will contribute to agricultural sustainability by: (i) reducing the need to improve soil P status to higher levels to achieve similar productivity, a strategy which is also more demanding regarding maintenance levels of P; and (ii) increasing the efficiency of use of the applied P, which is a non-renewable resource. Moreover, P-efficient crops would bring the economic rates of applied P within reach of smallholder farmers who might otherwise not use fertilisers.

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