



1 ~~Effects of Improved Pastures and Phosphorus Inputs on Phosphorus~~
2 **Transformations in a Colombian Oxisol**

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13 **Abstract**

14
15 The effect of improved grass-only (*Brachiaria decumbens*) (GO) and grass-legume (+
16 *Pueraria phaseoloides*) (GL) pasture on P transformations in an Oxisol was investigated
17 using native savanna (SA) as the control treatment. Top soil samples (10 cm) were taken in a
18 15 year old field experiment in the Eastern Plains of Colombia designed to test improved
19 pastures with legumes as a low input system to raise animal production on acid, infertile soils.
20 Total P inputs (1978-1993) were 0, 103 and 106 kg P ha⁻¹ in SA, GO and GL, respectively. A
21 sequential fractionation method was used to determine different organic (P_o) and inorganic P
22 (P_i) fractions. Organic C and N contents were measured in these extracts in order to
23 characterize P_o fractions more completely. P budgets were estimated for the different pasture
24 types. The quantity of labile P_o extracted with water or 0.5 M NaHCO₃ was only slightly or
25 not affected by the pasture type. P_o extracted in 0.1 M NaOH was increased in the GL
26 pasture, supporting results indicating that this fraction, in tropical soils, shows changes in

1 land use within a relatively short time scale. Inorganic fractions were increased under
2 improved pastures, and the increase was more marked for the GL than the GO pasture.
3 Differences in P fractions between treatments largely showed in total contents across all
4 fractions, rather than in relative distributions. This suggests that the initial partitioning of
5 applied P among soil P fractions was not greatly influenced by improved pasture species
6 either in GO or in GL systems. Significantly, the observed absolute increases in fractions and
7 total soil P occurred almost entirely in the GL pasture. The increase in labile P_i could not be
8 explained by the P input through fertilizers or the positive P budget because these were
9 similar for GO and GL pastures. Legumes appeared to enhance P fertility. It is assumed that
10 the N input by the legumes via biological N fixation caused a more efficient P cycling in
11 connection with enhanced soil biological activity and modified chemical soil characteristics
12 favouring P availability. C and N contents in the different extractants used to assess P_o
13 followed the same patterns as the P content, i.e. were increased in the GL pasture. The
14 C/N/ P_o ratios were rarely affected by the pasture type, showing that the effect on the P_o , C
15 and N content occurred in concert. However the C/N/ P_o ratios varied from one extractant to
16 another. C/ P_o ratios were high when compared to values known from literature. They indicate
17 a need to revise the critical C/ P_o ratios currently used in the P submodel of Century in order
18 to adapt it to conditions met in tropical soils. As the low inputs of P applied in the GL pasture
19 led to an increase of labile P_i fractions, an efficient P cycling through different P pools occurs
20 despite the high C/ P_o ratios, the substantial P sorption capacity and the still low labile P
21 contents in tropical pasture soils. Soil phosphatase activity was higher in improved pastures
22 than native savanna soils and indicates for all treatments the important role of organic P in P
23 cycling. The integrated consideration of P fractions, total P and P budgets suggests that P
24 losses from the 0-10 cm layer occur especially in the GO pasture. On the other hand, the GL
25 pasture offer, with respect to soil P fertility, a sustainable agricultural system requiring only
26 low inputs of P fertilizers, in order to maintain an equilibrated P budget.

1 INTRODUCTION

2

3 Savannas cover about 45% of the land or 243 million ha in Latin America. Traditionally
4 they are used for extensive grazing and ranching. Low nutrient reserves, aluminum toxicity or
5 acidity without Al toxicity, and high P fixation by Fe oxides are the main chemical soil
6 constraints for agricultural production in the acid savannas (Sánchez and Logan, 1992). In
7 the development of agricultural systems replacing native savanna, sustainability is a major
8 aim. The search for sustainable practices in agriculture requires a long-term field and
9 laboratory approach to determine the complex interactions of soils, plants, animals, climate
10 and management (Army and Kemper, 1991). In 1978, field experiments with improved
11 pastures meeting this need were started in Carimagua, Eastern Plains of Colombia (Lascano
12 and Estrada, 1989), and are at present the subject of interdisciplinary research (CIAT, 1992).

13 Phosphorus is among the nutrients most limiting plant production in the acid savannas. P
14 deficiency in livestock grazing in native savanna is widespread, affecting especially
15 reproduction performance (Fisher et al., 1992). Acid soil tolerant pasture germplasm cannot
16 be established without additions of purchased P and there are insufficient amounts available
17 in the unamended soils to improve recycling (Thomas et al., 1994). The input of the large
18 amount of fertilizers required to amend these soils (von Uexküll and Mutert, 1993) is not
19 possible because of economic and infrastructural constraints and is questionable for
20 ecological reasons: the area is an important watershed (Lewis and Saunders, 1989) affected
21 by soil erosion (Piá, 1988), and an increase in P content of the eroded material would
22 drastically increase fluvial P fluxes. Consequently, improved use efficiency of P applied in low
23 amounts as fertilizers and of P from different soil pools is important for sustainability in the
24 sense of an ongoing, resource conserving and environmentally safe agricultural system.

25 In the soil, P exists in different organic and inorganic forms. Organic P (P_O) constitutes
26 15 to 80% of total soil P (Dalal, 1977). Routine soil testing which aims to determine P fertilizer

1 requirements currently assesses P_i only (Olsen and Sommers, 1982). Several studies show
2 the importance of soil P_o mineralization in providing available P_i in the temperate (Hedley et
3 al., 1982; Tiessen et al., 1983; Sharpley, 1985; Stewart and Tiessen, 1987) and tropical
4 zones (Tiessen et al., 1992; Ball-Coelho et al., 1993). Organic P recycling via plant residues
5 (Friesen and Blair, 1988; Thibaud et al., 1988; Umrít and Friesen, 1994) and animal excreta
6 (Campbell et al., 1986; Oberson et al., 1993) is known to contribute readily to plant available
7 P. However, there is no known analytical procedure to satisfactorily assess the availability of
8 soil P_o (Tiessen et al., 1994). The application of a chemical P fractionation method showed
9 evidence of the contribution of P_o to plant nutrition when applied to soils of long term
10 research sites (Tiessen et al., 1983; Oberson et al., 1993). At the same time, the difficulty in
11 assigning availability of P_o to its extractability with different chemicals was shown.
12 Furthermore, the inadequacy of routine soil tests to determine P_i availability is well known
13 (Fardeau et al., 1988). In tropical soils that show rapid P transformations and substantial P
14 sorption, extraction methods for P fertility have been less successful, and fertilizer responses
15 have been erratic. The need to look at P cycling rather than available pool size is well
16 recognized (Tiessen and Moir, 1993), especially for perennial plants and natural ecosystems.

17 Improved pastures using acid-tolerant grass and legume varieties have resulted in a 10
18 to 15-fold increase in beef production per ha in field experiments in Carimagua (Lascano and
19 Estrada, 1989; Thomas et al., 1994). The fact that this dramatic production increase was
20 obtained with modest P fertilizer inputs raises questions about the perceived inefficiency of P
21 fertilizer inputs on high-weathered, high P-sorbing soils, and about transformations of soil and
22 fertilizer P occurring when native savanna is replaced by improved grass-only or grass-
23 legume pastures.

24 The present investigation attempts to answer these questions by means of sequential
25 chemical P fractionation to assess the significance of different P_o and P_i fractions and
26 estimated P budgets for native savanna and improved pasture soils. Comparison of a grass-

1 only (GO) pasture, a grass-legume (GL) pasture and native savanna (SA) will elucidate the
2 effects of improved pastures on various P fractions. The fractionation method was
3 augmented with the characterization of the C/N/P_o ratios of the organic matter extracted
4 during different steps. Methods for C and N determination in soils and water were modified to
5 overcome chemical and concentration problems of each extractant. The ratios are discussed
6 in relation to the availability of P_o fractions. Soil phosphatase activity was included to give an
7 indication of the P_o mineralization potential (Oberson et al., 1993).

8 Data are discussed in terms of an improved understanding of P transformations in soils
9 under improved pastures and in terms of their significance for models simulating soil organic
10 matter dynamics, in particular the Century model (Parton et al., 1988; Parton et al., 1989).
11 The usefulness of different P_o and P_i fractions as sustainability indicators is evaluated.

12

13

14 **MATERIALS AND METHODS**

15

16 **Description of the field experiment**

17

18 Soil samples were taken in a long-term pasture experiment established in 1978 at the
19 ICA-CIAT (Instituto Colombiano Agropecuario - Centro Internacional de Agricultura Tropical),
20 Carimagua research station, Meta, Colombia (4° 30' N, 71° 19'W, 150 masl). The area is
21 representative of the well drained savannas. Mean temperature is 26° C and mean annual
22 rainfall is 2200 mm with a distinct dry season from December through March. The soils are
23 Oxisols (tropeptic haplustox isohyperthermic) with medium to high P sorption capacity (Juo
24 and Fox, 1977; Sánchez and Uehara, 1980), a silty clay loam texture (39% clay, 42% silt,
25 19% sand) and a bulk density of 1.3 g cm⁻³ (Gijssman and Thomas, 1994). Soil chemical
26 characteristics are summarized in Table 1.

1 The following treatments were included in the study:

- 2 1. Native savanna (SA): burned every 16 months and grazed with 0.25 steer ha⁻¹.
- 3 2. Grass-only pasture (GO): *Brachiaria decumbens* cv Basilisk grazed with 1 steer ha⁻¹
4 during the dry and 2 steers ha⁻¹ during the rainy season.
- 5 3. Grass-legume pasture (GL): *Brachiaria decumbens* cv Basilisk with *Pueraria*
6 *phaseoloides* CIAT 9900 (Kudzu) grazed at rates equal to the GO treatment. The
7 average legume content in the period from 1979-93 was 40% (C. E. Lascano, 1994,
8 personal communication).

9 In subsequent discussions, 'improved pastures' will refer to the sown GO and GL
10 treatments which differ from the SA treatment.

11 As the 1 ha plots of improved pastures are not replicated, they were divided into two
12 (pseudo) 0.5 ha replicates in order to check for spatial variability within the treatments. In the
13 SA treatment, two 0.5 ha fields were laid out and sampled as for the improved pastures. More
14 detailed information about pasture management is presented in Tergas et al. (1984) and
15 Lascano and Estrada (1989). Total nutrient input through fertilizers, applied during 1978-
16 1993, is presented in Table 2 (C. E. Lascano, 1994, personal communication). SA was never
17 fertilized.

18

19 **Soil sampling and soil preparation**

20

21 Soil sampling (0-10 cm) was carried out on September 16, 1993, during the rainy season
22 using an 8 cm diameter auger. In each treatment and replicate, 4 samples randomly
23 distributed over the field were taken and bulked into 1 sample. Four of these bulked samples
24 were taken per plot, resulting in 8 samples per treatment. Soil samples were air-dried and
25 sieved to pass a 2 mm sieve before chemical analysis according to standard methods (Table
26 1). Sequential P fractionation and the determination of total carbon (CT) were done on 1 mm

1 sieved samples.

2

3 **Methods of soil analysis**

4

5 ***Methods of soil P analysis***

6 Available P was estimated by the Bray II method (Olsen and Sommers, 1982). Total soil
7 P (P_T) was determined by perchloric acid digestion (Olsen and Sommers, 1982).

8 The sequential P fractionation method of Hedley et al. (1982) was applied as modified by
9 Tiessen and Moir (1993). This procedure attempts to quantify labile P_i, Fe- and Al-
10 associated, and Ca-bound P_i as well as the labile and more stable forms of P_O using the
11 following extractants: H₂O with anion exchange resin, 0.5 M NaHCO₃, 0.1 M NaOH, 1.0 M
12 HCl, hot conc. HCl. The soil remaining at the end is digested with perchloric acid to determine
13 residual P. Inorganic P in extracts was determined by the molybdate-ascorbic acid method
14 (Murphy and Riley, 1962) adapted by Tiessen and Moir (1993). Total P in the H₂O, NaHCO₃,
15 NaOH and hot HCl extracts was measured after digestion with K₂S₂O₈ (Bowman, 1989).
16 Organic P was calculated as the difference between total P and P_i (total P in the H₂O is
17 equal to P_O since P_i is removed by the resin).

18 Fractions are abbreviated as follows: H₂O-P_O; Resin-P_i; Bic-P_i, -P_O; NaOH-P_i, -P_O; HCl-
19 P_i; HCl_{hc}-P_i, -P_O; Resid-P_t.

20

21 ***Determination of the C content in P fractionation extracts***

22 Organic C in H₂O-, NaHCO₃-, NaOH- and HCl_{hc}-extracts was determined according to
23 the method proposed by Heanes (1984) for organic C determination in soils, modified as
24 follows:

25 For the water and the alkaline extracts, 49 g potassium dichromate (K₂Cr₂O₇) were
26 dissolved and diluted to 1 L with deionised water. Sucrose standards containing 0.2 mg C

1 mL⁻¹ were prepared in the corresponding matrices. Aliquots of the extracts (10 mL of the
2 H₂O- and NaHCO₃-extracts, 2.5 mL of the NaOH-extract) were pipetted into 25 mL flasks.
3 Similarly, a standard series containing 0, 0.5, 1.0, 1.5, 2.0 mg C/25 mL-flask was prepared by
4 pipetting aliquots of the sucrose standard in the appropriate matrix and adjusting the volumes
5 to 10 mL with suitable volumes of the corresponding matrix solution. Then, 1.25 mL of
6 K₂Cr₂O₇-solution and 2.5 mL conc. H₂SO₄ were added the each flask. After cooling and
7 swirling the contents, flasks were capped lightly with aluminum foil and heated in a preheated
8 oven at 135°C for 30 min. When cool, solutions were made to volume, shaken and read on a
9 spectrophotometer at 600 nm using a cell of 4 cm pathlength. For the HCl_{hc} extracts, a
10 solution of 12.0 g K₂Cr₂O₇ in 100 mL deionised water (saturation point) was used to prevent
11 decomposition of Cr₂O₇ in the acid extracts. A 7.5 mL aliquot of extract was pipetted into a
12 25 mL flask and a standard series containing 0, 0.2, 0.5, 1.0, 1.5 mg C/25 mL-flask in matrix
13 according to extract was prepared. Thereafter, 10 mL deionised water (to keep the
14 concentration of the acid below 1.5 M (Kolthoff and Sandell, 1952) and 2.5 mL of K₂Cr₂O₇-
15 solution (but no conc. H₂SO₄) were added and the procedure was completed as described
16 for the other extracts. Linear standard curves were obtained for all matrices. Slopes for the
17 H₂O and NaOH were equal, whereas the slope of the Bic standard was slightly steeper. A
18 different slope was obtained for the HCl_{hc} matrix.

19 C remaining in the soil residue (Resid-C) was estimated as difference between total C
20 [(CT; determined by combustion in a LECO CR-12 furnace with infrared detection of CO₂)
21 and the sum of C measured in the different extracts.

22

23 ***Determination of the N content in P fractionation extracts***

24 Total N in H₂O-, NaHCO₃- and NaOH-extracts was determined by digestion with
25 potassium persulfate in an autoclave (Ebina et al., 1983). Glycine was used as a source of
26 organic N to establish a standard curve. Standards containing 0-10 mg N L⁻¹ as glycine in

1 the corresponding matrix were prepared in 50 mL erlenmeyer flasks. To 10 mL of standards
2 or extract, approx. 0.6 g $K_2S_2O_8$ were added to the H_2O - and $NaOH$ - samples and 1.2 g
3 $K_2S_2O_8$ to the $NaHCO_3$ extracts to ensure acidic conditions. Samples were covered with
4 aluminum foil and autoclaved for 1 hour. After cooling, 0.2 g Devarda's alloy was added to
5 convert nitrate to ammonium (Raveh and Avnimelech, 1979). Extracts were filtered the
6 following day and NH_4 was determined colorimetrically on an autoanalyser.

7 Total N in the HCl_{hc} extracts was determined after Kjeldahl digestion on an
8 autoanalyser. To confirm complete recovery, glycine standard solutions prepared in the
9 corresponding matrix were carried through the complete process.

10 N in the perchloric acid digest of the soil residue was read as NH_4 -N on an autoanalyzer.
11 Total N (NT) was determined by Kjeldahl digestion with a colorimetric autoanalyzer finish.

12

13 ***Phosphatase activity***

14 Acid soil phosphatase activity was measured according to the method of Tabatabai
15 (1982) at pH 6.5, using 1 mm sieved soil samples.

16

17

18 **Statistical data analysis**

19

20 The effects of treatment, experimental error (plots within treatments) and sampling error
21 (samples within plots) were tested by a hierarchical analysis of variance. $C/N/P_0$ ratios were
22 analysed after logarithmic transformation in order to normalize the distribution of residuals. As
23 the experimental error was not different from sampling error for any of the variables analysed,
24 treatment effects were tested against the pooled variance of experimental and sampling
25 error. If the F test was significant ($P \leq 0.05$) the means were compared by Tukey's multiple
26 range.

1 As previously described, 8 samples were taken and analysed per treatment. Outliers
2 were only omitted if the examination of the residuals proposed by Anscombe and Tukey
3 (1963) allowed doing so. Following this procedure, 1 of 8 samples of the GL treatment was
4 replaced by a missing value for all P data because the P content found was very high even
5 for this group, probably as a result of contamination with dung during the soil sampling in the
6 pasture.

7

8

9 RESULTS AND DISCUSSION

10

11 Effects of improved pastures on organic soil P fractions

12

13 While both P_i and P_o fractions were affected by improved pasture treatments (Table 3),
14 the GL pasture induced more pronounced changes than the GO pasture when compared to
15 the SA. This was a consequence of the overall significantly higher total P (SumPT and PT;
16 Table 3) content of the GL pasture.

17 In all treatments, approximately 32% of the total extractable P (SumPT) was in P_o
18 fractions. NaOH- P_o formed the most important extracted P_o fraction. Using the same
19 method, Tiessen and Moir (1993) found 23% and 15% of total P in organic fractions in
20 Brazilian Oxisols under a native thorn forest and after 5 years of cultivation, respectively.

21 The importance of P_o in the soil solution is reflected in the almost equal amounts of P_o
22 and P_i extracted in the resin- H_2O step. In temperate grassland soils especially, P_o in the soil
23 solution is usually more important than P_i with a reported range of 0.28-0.57 mg P L⁻¹ (Dalal,
24 1977). Although our results (Table 3) are not directly comparable with this range (being
25 obtained at a soil:water ratio of 1:60), they are very high and demonstrate the need to assess
26 P_o in the soil solution of savanna pastoral systems. Moreover, since biomass P has been

1 found to be a major factor controlling P_o and P_i solution concentration in grassland topsoil
2 (Seeling and Zasoski, 1993), attention must be given to the relation between microbial P and
3 P concentration in solution.

4 Labile Bic- P_o was not affected by the conversion of native savanna into improved
5 pastures while NaOH- P_o was increased under the 14-year-old GL pasture but not the GO
6 pasture. Consequently, contrary to expectations, modifications in P_o were not consistently in
7 step with the increases in organic C (Table 5).

8 The results obtained for Bic- P_o and NaOH- P_o support the revised interpretation of these
9 two fractions for tropical soils (Tiessen et al., 1994). In extracts of temperate soils Bic- P_o was
10 shown to contain mainly labile actively cycling P_o compounds (Bowman and Cole, 1978;
11 Tiessen et al., 1983), while NaOH- P_o was interpreted as moderately labile P_o bound mainly
12 to fulvic and humic acids (Bowman and Cole, 1978). The latter fraction was considered to
13 reflect the slower, long-term transformations of soil P_o occurring during soil formation or
14 prolonged cultivation (Tiessen et al., 1983). However, more recent results obtained for
15 temperate (Gahoonia and Nielsen, 1992; Oberson et al., 1993) as well as tropical soils (Ball-
16 Coelho et al., 1993) show that this distinct separation does not necessarily reflect processes
17 going on in the field. In an Oxisol, about six years of cultivation reduced NaOH- P_o while Bic-
18 P_o levels remained constantly low (Tiessen et al., 1992). Similarly, the buildup of P_o as a
19 result of fertilizer additions was only reflected in the NaOH- P_o fraction. Thus, Bic- P_o appears
20 to be at a constant level regardless of the cropping history in some tropical soils while the
21 NaOH- P_o fraction reflects the overall changes in soil organic matter and P_o levels when the
22 soil is stressed by cultivation and net P export. This fraction may therefore represent a
23 relatively active reservoir (source or sink) of P under tropical conditions (Tiessen et al., 1992).
24 Differences between treatments, however, reflect exclusively net changes. Given the fact that
25 climatic conditions of the tropics favour rapid nutrient turnover, it is not logical to consider only
26 differences between treatments as a reflection of P turnover in a given fraction. The

1 assessment of gross mineralization requires other approaches such as tracer techniques.

2 The residual P_f of the original fractionation scheme (Hedley et al., 1982) has sometimes
3 shown relatively short-term transformations despite its recalcitrance with respect to chemical
4 extractants (Tiessen et al., 1994; Oberson et al., 1993). This was attributed to the
5 unextractability of P held in particulate organic debris although this P may be rapidly
6 mineralized by soil fauna and flora. The hot acid digest was introduced to extract part of
7 inorganic and organic residual P. In the present study, both improved pastures showed a
8 nonsignificant trend of increasing $HCl_{HC}-P_O$ (Table 3).

9 Since only 62% of the C was recovered from the different fractions (mean over all
10 treatments, Table 5), it may be assumed that residual P_f contained additional P_O which
11 resisted hot HCl extraction as well. To investigate this assumption, an additional 2 samples
12 per treatment were again subjected to sequential P fractionation. The soil residue was
13 extracted with conc. HF to extract residual P_i and afterwards digested with conc. H_2SO_4 and
14 H_2O_2 (Tiessen and Moir, 1993) to assess residual P_O . These preliminary results suggest that
15 70% of Resid- P_f is organic P. At present, neither the nature nor the fate of these organic
16 compounds is known.

17 The legume *Pueraria phaseoloides* decomposes at rates similar to the grass *Brachiaria*
18 *decumbens* (Thomas and Asakawa, 1993). Therefore, it is unlikely that the increase in
19 extractable soil P_O was due to inert plant material, despite the higher lignin contents in
20 tropical legumes than grasses. Given the increase in labile P_i fractions, especially in the GL
21 pasture, P_O in plant residues and animal excreta seems to be recycled efficiently. This is
22 supported by the observation of higher acid phosphatase activity in improved pastures than in
23 native savanna, the treatment mean and SE values being 181 ± 8 , 213 ± 14 , 239 ± 17 mg *p*-
24 nitrophenol $kg^{-1} h^{-1}$ for SA, GO and GL, respectively. In all treatments, acid phosphatase
25 activity was somewhat higher than found in similar Brazilian soils reported by Feller et al.
26 (1994) using the same method.

1
2 **Effects of improved pastures on inorganic soil P fractions and on P availability**

3
4 All extractable inorganic fractions were increased in the GL pasture but not the GO
5 pasture (Table 3).

6 Resins assess exchangeable labile P_i (Cooperband and Logan, 1994), while 0.5 M
7 NaHCO_3 extracts a P_i fraction which is considered plant available (Bowman and Cole, 1978).
8 Thus, the modifications observed in the GL pasture in these fractions indicate an
9 improvement in P availability which is also reflected in the results of the Bray II-P soil test
10 values (Table 3). The quantity extracted with the resin strips was higher than Bray II-P.
11 Although their content is still very low, the increase in labile P_i fractions is surprising given the
12 low P inputs made by fertilizers (Table 2) and the medium to strong P sorption capacity of the
13 soil.

14 $\text{NaOH-}P_i$ represents Fe- and Al-associated P (Williams et al., 1980). In acid soils in
15 particular, it is not considered a completely separate pool from Bic- P_i (Tiessen and Moir,
16 1993). Increased concentrations of $\text{NaOH-}P_i$ in the GL pasture were associated with the
17 overall increase in total P in this treatment (Table 3).

18 HCl (1 M) extracts mainly Ca-bound P in soil (Williams et al., 1971) and the very small
19 amounts found for all treatments reflect the highly weathered nature of this soil and the
20 absence of Ca minerals. This extraction step would only be of interest in acid savanna soils in
21 which the fate of applied rock phosphate is of concern or large amounts of lime have been
22 applied.

23 P_i extracted with hot concentrated HCl was the dominant P fraction in the Oxisol of the
24 Carimagua experimental site. It is considered as highly recalcitrant P_i (Tiessen and Moir,
25 1993) and, despite the higher levels of labile P_i and P_o in the GL pasture soil, this fraction
26 was a sink for significantly greater amounts of applied P than the same fraction in the GO

1 pasture (Table 3).

2 In all treatments, differences in P fractions were largely in absolute values rather than
3 relative terms. This suggests that the preliminary partitioning of applied P among soil P
4 fractions was not greatly influenced by improved pasture species either in GO or in GL
5 systems. Significantly, the observed absolute increases in fraction sizes, including fractions
6 considered as readily available, occurred almost entirely in the GL pasture.

7

8 **P budgets in native savanna and improved pastures**

9

10 P budgets were estimated to determine the relation between P input in improved
11 pastures and P output via beef cattle, and to better understand the modifications in the size of
12 P fractions or total P that occurred especially in the GL pasture. P budgets were calculated by
13 subtracting the P removed from the system by animals from the P applied in mineral fertilizer
14 (Table 2). P exported with the animals was assumed to be 8 g P per kg of live weight gain
15 (LWG) (NRC, 1984). LWGs in the improved pastures were 200 kg ha⁻¹ yr⁻¹ for GO and 300
16 kg ha⁻¹ yr⁻¹ for GL pastures (Lascano and Estrada, 1989), while in savanna a LWG of 15-20
17 kg ha⁻¹ yr⁻¹ was assumed (Fisher et al., 1992).

18 Positive P budgets were obtained for both improved pastures while a small negative
19 budget was found for the unfertilized SA (Table 4). Clearly, differences in PT as well as
20 available P fractions between the GO and the GL pasture were not due to differences in P
21 budgets.

22 The calculated differences in the P budget are 81 kg P ha⁻¹ between GO and SA and 72
23 kg P ha⁻¹ between GL and SA (column 4, table 4). Assuming that all (non-exported) applied
24 P remained in the 0-10 cm surface soil layer and using a bulk density of 1.3 g cm⁻³, the
25 measured PT differences (column 5, table 4) are smaller than the values estimated from the
26 budget for the GO as well as for the GL treatment. Especially for GO, the discrepancy

1 (column 6, table 4) clearly exceeds differences that might be explained by analytical errors.
 2 One possible explanation for the observed discrepancies is that the P budgets were much
 3 less than estimated for both improved pasture types. However, overestimation of the P
 4 budget could only occur by underestimation of P exported in animal LWG, and it is unlikely
 5 that the error would be so large. Moreover, P exported would be expected to be similar for
 6 both systems or perhaps even greater from GL pastures given the higher P content in
 7 legumes than grasses (Thomas and Asakawa, 1993). The alternative explanation is that P
 8 moved out of the surface soil into the soil profile and that there was a larger net movement of
 9 P out of the top soil layer in the GO pasture compared to the GL pasture.

10 Net transfer of nutrients between the surface soil and subsurface layers is the sum of a
 11 number of complex and interacting processes including leaching, phloem and xylem transport
 12 in root tissue and the effects of soil faunal activity. It is very improbable that any significant
 13 movement of inorganic P would have occurred through leaching, given the substantial
 14 sorption capacity of this soil. However, losses of soluble organic P as well as of particulate P
 15 were reported by Lopez-Hernandez (1991) for flooded savanna. These losses may also
 16 occur despite the fact that the experimental site is located in well drained savanna,
 17 considering the high rainfall intensity, the high P_o contents in the water of the resin extraction
 18 step (Table 3) and the fine texture of the soil. The results suggest that these losses might
 19 have been higher in the GO than the GL pasture.

20 The recent observation of C accumulation at depth under improved tropical pastures
 21 (Fisher et al., 1994) suggests another sink for the missing P in the budget. An investigation
 22 focusing on the modification of P contents in deeper soil layers under the improved pastures
 23 presented in our study could elucidate the fate of P concomitant to possible C sequestration.

24

25 C/N and C/ P_o ratios of different organic P fractions

26

* and the very low P_i concentrations in soil solution (\rightarrow removal
 H. Tresen 18.01.95 \rightarrow I will indicate them)

1 All C in the different extracts of the sequential P fractionation method (Table 5) is
2 assumed to be in organic form since Oxisols are generally devoid of weatherable primary
3 minerals. The validity of the method proposed to determine C contents in the different
4 extracts was evaluated by fractionating an additional two samples per treatment and
5 measuring Resid-C. Resid-C was measured by CT determination (LECO) on the dried soil
6 residue remaining after the hot HCl step. The means were 7.5, 6.6 and 7.6 mg C g⁻¹ soil for
7 the SA, GO and GL treatment, respectively. These results coincide reasonably well with
8 calculated Resid-C (Table 5), indicating satisfactory C determination in the previous steps.

9 The N contents of the extracts (Table 6) are assumed to represent organic N; any NO₃
10 would be removed by the resin step and NO₃ concentrations in the eluate were not
11 detectable. NH₄ contents of a water extract at the same soil-water ratio (1:60) as used in the
12 fractionation procedure were 10.5, 7.2 and 14.1 mg NH₄-N kg⁻¹ (mean of 2 samples of the
13 SA, GO and GL treatment, respectively). These contents represent 10-28% of H₂O-N (Table
14 6), but less than 1% of total N. The sum of N (SumNT) assessed in the extracted fractions
15 and in the soil residue shows good N recovery when compared to NT determined by Kjeldahl
16 digestion (Table 6).

17 The pasture type affected the C (Table 5) and N content (Table 6) of the extracts. The
18 increased NT content in the GL pasture was reflected in all fractions although the effect was
19 not always significant. Similar trends were evident for organic C, but the effects were
20 statistically less clear.

21 Differences in the composition of soil organic matter extracted in the different steps or
22 remaining in the soil residue are illustrated by their C/N and C/P₀ ratios (Table 7). Since
23 pasture type did not significantly affect these ratios, only mean values for each extract are
24 presented. In general, the C/N/P₀ ratios (Table 7), especially C/P₀, were high when
25 compared to values known from the literature which are mainly based on studies on
26 temperate soils. Black and Goring (1953) suggested that the organic matter of mineral soils

1 contains C/N/P_o in the ratio of about 110:9:1. Taking organic N as 10, Barrow (1961)
2 calculated average values for organic C ranging from 71 to 229 while P_o ranged from 0.15 to
3 3.05. This greater variability could be in part a consequence of limitations of the analytical
4 procedure for total soil P_o (Condrón et al., 1990).

5 C/N ratios varied more between extractants than C/P_o (Table 7). Assuming that 70% of
6 Resid-P_t was organic P, the ratio Resid-C/Resid-P_o was 253. Consequently, C/P_o ratios
7 varied by a factor 2 among extractants, C/N ratios by a factor 4.

8 The C/P_o ratio in soil and plant residues added to soil has been used to predict net
9 immobilization and mineralization in soil with P_o mineralization occurring at ratios of 200 or
10 less, and P_i immobilization when ratios are 300 or more (Dalal, 1977). Consequently, fertilizer
11 P added to any treatment of the present study would be immobilized in organic matter.
12 However, the increase in available inorganic P fractions (Table 3), especially in the GL
13 pasture, occurring at the same time as an increase in total C and N (Table 5 and 6), suggests
14 an inconsistency in the principle based on C/P_o index. Assuming an average C content of
15 45% in plant material, data from Thomas and Asakawa (1993) show that plant litter of
16 improved grass and legume species has a C/P ratio ranging from ca. 400 to 2700.
17 Consequently, wider C/P_o ratios in these soils are likely an indicator of recent organic
18 material, and therefore an indicator of P_o with a high availability when is mineralized
19 concomitantly to C and N, driven by the need for energy (McGill and Cole, 1981). The high
20 phosphatase activity, in all treatments indicates the importance of biochemical or biological
21 processes in P_o mineralization.

22 Based on the high C/P_o ratios observed in the present study, not only in stable fractions
23 but also in labile P_o fractions, a re-evaluation of the critical C/P_o concept is required,
24 especially when used as a parameter for modelling P turnover, eg. in Century (Parton et al.,
25 1988). This soil organic matter model was developed to simulate the dynamics of C, N, P and
26 S in cultivated and uncultivated grassland soils of the temperate zone. As the model is a

1 useful tool to combine the effects of different factors on soil organic matter dynamics,
2 attempts are made to modify it for the needs of the tropical zone. Different pools of the N and
3 P submodel of Century (Parton et al., 1988; Parton et al., 1989) are distinguished by C/N and
4 C/P_0 ratios, respectively. C/N ratios ranging from 8 to 25 are assigned to N pools resulting in
5 N mineralization, whereas structural N with a C/N ratio of 150 results in N immobilization
6 (Parton et al., 1989). P pools with C/P_0 ratios ranging from 20-200 are supposed to be
7 mineralized, and structural P with $C/P_0 = 500$ is said to immobilize P. With respect to the C/N
8 ratios of the N pools of Century, all fractions contain organic matter which might contribute to
9 N mineralization (Table 7). However, all C/P_0 ratios are high. No fraction would fit into the
10 pool of active soil P ($C/P_0 = 30-80$), and most values are over the critical limit of 200.

11

12 **Factors enhancing P availability in GL pastures**

13

14 For many of the variables included to investigate P transformations, GL shows a more
15 distinct separation from SA than GO does. Increases in P_i fractions considered as readily
16 plant available show that P added to the soil via fertilizer, plant litter and animal excreta
17 cycles more efficiently in the GL pasture. Explanations for the fact that only small P inputs via
18 fertilizers enhanced P cycling in the GL more than in the GO pasture may be found in the
19 differences in soil floral and faunal activity as well as by the intervention of plants in P cycling.
20 Macrofauna are major players in the mixing of soil between upper and lower layers of the soil
21 profile. Macrofaunal biomass in the GL treatment was twice that of the GO treatment which
22 was double that of SA (Decaëns, 1993). P availability is apparently enhanced in casts of
23 earthworms (Lopez-Hernandez et al., 1993), which are the dominant macrofaunal species in
24 these treatments (Decaëns, 1993). Lavelle et al. (1993) estimated that 60% of the soil organic
25 matter in the upper 10 cm of an Ivory Coast Oxisol was ingested annually by earthworms.
26 Earthworm activity, therefore, must surely play a significant role in maintaining and enhancing

1 P availability in the improved GL pastures of this study.

2 The greater importance of processes linked to biological activity are also indicated by the
3 slightly higher phosphatase activity in GL than GO pastures. Furthermore, preliminary results
4 (data not shown) suggest that pasture composition influences soil microbial P content.
5 Microbial P was larger in the GL pasture compared with GO, which in turn was slightly higher
6 than SA. Microbial P is considered to be the second most active P pool in soil (Stewart and
7 Tiessen, 1987) after solution P.

8 Root growth and characteristics may also affect P cycling efficiency. Improved pasture
9 species (grasses and legumes) are considerably more deep-rooted than native savanna
10 species (CIAT, 1993; Rao et al., 1992). Deeper roots may absorb *P in situ* and 'pump' it to the
11 surface. In this respect, legumes may be more efficient cyclers, or at least promote more
12 efficient cycling in mixed pastures, than grasses. Evidence of this may be seen in the
13 comparatively higher cation concentrations (especially Ca) in the surface soil of the GL
14 pasture (Table 1). Table 6 also shows an important increase in total N which is a limiting
15 nutrient in the savanna soils. For instance, on clayey savanna soils near those investigated in
16 the present study, P applications only led to increased P concentrations in plant tissues and
17 increased forage production when N and K were applied as well (Fisher et al., 1992).
18 Moreover, Rao et al. (1994) report on modifications of soil organic matter as a consequence
19 of the introduction of legumes. Thus, the pumping effect of the plant on P cycling and greater
20 P availability would be higher in the presence of legumes than without in accordance with the
21 higher nutrient contents in their tissue.

22 In summary, therefore, initial low P inputs through fertilizers (Table 2) and N input by
23 legumes have enhanced nutrient cycling. Excreta from grazing livestock make a more
24 important contribution (Thomas, 1992) to the nutrient enrichment in the top most soil layer of
25 improved pastures than in the SA as a result of increased plant production, stocking rate and
26 higher nutrient contents especially in legumes. Together with the plant litter, excreta lead to

1 improved nutrient conditions for soil flora and fauna. As a result of interactions between
2 chemical and biological soil properties, P availability is increased. Similar results have also
3 been found for potassium (Rao 1994, unpublished results).

6 CONCLUSIONS

8 The quantities of water-soluble P_0 were remarkable when compared to values known
9 from literature. They were slightly higher in both of the improved pastures than the in native
10 savanna. Labile Bic- P_0 was not affected by the pasture type. Consequently, this fraction did
11 not reflect the changes in soil organic matter quantity observed in the improved pastures. As
12 known from other field studies, the observation that labile fractions do not reflect
13 modifications in the farming system does not necessarily mean that they are not involved into
14 short term dynamics. Temporal fluctuations in these fractions should be assessed in addition
15 to gross mineralization of organically bound P. The increase in NaOH- P_0 in the GL pasture
16 supports findings of other studies on tropical soils (Tiessen et al., 1992) showing that this
17 fraction may also react in a relatively short term towards changes in land use.

18 Despite the medium to strong P sorption capacity of the soil and the low P inputs from
19 fertilizers, labile P_i fractions increased in the GL pasture. Apparently, the presence of the
20 legume with its ability of biological N fixation induced a modification of chemical soil
21 parameters and enhanced soil biological activity. This complex of chemical and biological
22 factors resulted in an enrichment of all P_i fractions in the 0-10 cm soil layer of GL pasture
23 compared to GO and SA, apparently due to increased nutrient cycling via excreta from
24 grazing animals and plant litter.

25 P budgets in both improved pasture types were highly positive in relation to animal
26 exports in beef. Although periodic applications of P fertilizer would be required in order to

1 correct for the P exported by animals, it is not clear from this study whether the current
2 fertilization strategy is simply maintaining labile P levels at their current level or is causing to
3 continued increase. Nevertheless, from the viewpoint of positive P budgets and increases in
4 most P fractions as well as PT, both systems so far appear to be sustainable. However, the
5 comparison of PT and the estimated P budget indicates P losses from the 0-10 cm layer
6 especially in the GO pasture. Consequently, the integrated consideration of P fractions, PT
7 and P budget shows that the GO pasture is less resource conserving than GL.

8 The C/N/P_o ratios depended on the extractant not on the pasture type. The C/P_o ratios
9 for all fractions were close to the value considered critical for P_i immobilization and were high
10 when compared to the values assumed for different P pools of the Century model. However,
11 neither inhibition of soil organic matter buildup nor immobilization of P_i into soil organic matter
12 occurred, as suggested by Barrow (1960), when the N input into the system increased
13 through the presence of legumes. Consequently, a highly efficient cycling of P was evident,
14 especially for the GL pasture. This suggests that C/P_o ratios of the P submodel of Century
15 attributed to pools of different turnover characteristics need to be revised before the model
16 can be used to simulate organic matter dynamics in tropical grassland soils.

17 Phosphatase activity was at a high level for all treatments, thus indicating the importance
18 of processes related to biological activity of soil fauna and flora as well as of plants. It also
19 shows the significance of organic P in the soil P dynamics of improved pastures and native
20 savanna. However, quantification of the role of organic P in P cycling requires other
21 methodological approaches. Isotopic tracers might provide a useful tool in determining more
22 directly the direction of P fluxes (into or out of organic pools) which would otherwise be
23 inferred from concurrent changes in other pools.

24

25

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1 REFERENCES

- 2
- 3 Anscombe, F.J., and J.W. Tukey. 1963. The examination and analysis of residuals.
4 Technometrics 5: 141-160.
- 5 Army, T.J., and W.D. Kemper. 1991. Support for long-term agricultural research. Agron. J. 83:
6 62-65.
- 7 Ball-Coelho, B., I.H. Salcedo, H. Tiessen, and J.W.B. Stewart. 1993. Short- and long-term
8 phosphorus dynamics in a fertilized ultisol under sugarcane. Soil Sci. Soc. Am. J. 57:
9 1027-1034.
- 10 Barrow, N. J. 1960. Stimulated decomposition of soil organic matter during the decomposition
11 of added organic materials. Aust. J. Agric. Res. 11: 317-330.
- 12 Barrow, N. J. 1961. Phosphorus in soil organic matter. Soils Fert. 24: 169-173.
- 13 Bowman, R.A. 1989. A sequential extraction procedure with concentrated sulfuric acid and
14 dilute base for soil organic phosphorus. Soil Sci. Soc. Am. J. 53: 362-366.
- 15 Bowman, R.A., and C.V. Cole. 1978. An exploratory method for fractionation of organic
16 phosphorus from grassland soils. Soil Sci. 125: 95-100.
- 17 Black, C.A., and C.A.I. Goring. 1953. Organic phosphorus in soils. p. 123-152. *In* W.H. Pierre
18 and A.G. Norman (ed.) Soil and fertilizer phosphorus in crop nutrition. Agron. 4,
19 Academic Press New York.
- 20 Campbell, C.A., M. Schnitzer, J.W.B. Stewart, V.O. Biederbeck, and F. Selles. 1986. Effect of
21 manure and P fertilizer on properties of a black chernozem in Southern Saskatchewan.
22 Can. J. Soil Sci. 66: 601-613.
- 23 CIAT. 1992. Pastures for the tropical lowlands. CIAT Publ. 211.
- 24 CIAT. 1993. Tropical forages biennial report. CIAT Working Document 166.
- 25 Condon, L.M., J.O. Moir, H. Tiessen, and J.W.B. Stewart. 1990. Critical evaluation of
26 methods for determining total organic phosphorus in tropical soils. Soil Sci. Soc. Am. J.
27 54: 1261-1266.
- 28 Cooperband, L.R., and T.J. Logan. 1994. Measuring in situ changes in labile soil phosphorus
29 with anion-exchange membranes. Soil Sci. Soc. Am. J. 58: 105-114.
- 30 Dalal, R.C. 1977. Soil organic phosphorus. Adv. Agron. 29: 83-117.

- 1 Decaens, T. 1993. Ecosystemes patures et amelioration des paturages naturels dans les
2 savanes d'amerique du sud. Memoire bibliographique de D.E.S.S. Universite XII Val de
3 Marne, Paris.
- 4 Ebina, J., T. Tsutsui, and T. Shirai. 1983. Simultaneous determination of total nitrogen and
5 total phosphorus in water using peroxodisulfate oxidation. *Water Res.* 17: 1721-1726.
- 6 Fardeau, J.C., C. Morel, and R. Boniface. 1988. Pourquoi choisir la méthode Olsen pour
7 estimer le phosphore assimilable des sols? *Agronomie* 8: 577-584.
- 8 Feller, C., E. Frossard, and M. Brossard. 1994. Activité phosphatasique de quelques sols
9 tropicaux à argile 1:1. Répartition dans les fractions granulométriques. *Can. J. Soil Sci.*
10 74: 121-129.
- 11 Fisher, M.J., C.E. Lascano, R.R. Vera, and G. Rippstein. 1992. Integrating the native
12 savanna resource with improved pastures. p. 75-99. *In* CIAT (ed.). *Pastures for the*
13 *tropical lowlands.* CIAT Publ. 211, Cali, Colombia.
- 14 Fisher, M.J., I.M. Rao, M.A. Ayarza, C.E. Lascano, J.I. Sanz, R.J. Thomas, and R.R. Vera.
15 1994. Carbon storage by introduced deep-rooted grasses in the South American
16 savannas. *Nature* 371: 236-238.
- 17 Friesen, D.K., and G.J Blair. 1988. A dual radiotracer study of transformations of organic,
18 inorganic and plant residue phosphorus in soil in presence and absence of plants. *Aust.*
19 *J. Soil Res.* 26: 355-366.
- 20 Gijsman, A., and R.T. Thomas. 1994. Aggregate size distribution and stability of an Oxisol
21 under legume-based and pure grass pastures in the eastern Colombian savannas. *Aust.*
22 *J. Soil Res.* (in print).
- 23 Gahoonia, T.S., and N.E. Nielsen. 1992. The effects of root-induced pH changes on the
24 depletion of inorganic and organic phosphorus in the rhizosphere. *Plant Soil* 143: 185-
25 191.
- 26 Heanes, D.L. 1984. Determination of total organic-C in soils by an improved chromic acid
27 digestion and spectrophotometric procedure. *Commun. Soil Sci. Plant Anal.* 15: 1191-
28 1213.
- 29 Hedley, M.J., J.W.B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic and organic
30 soil phosphorus fractions induced by cultivation practices and by laboratory incubations.
31 *Soil Sci. Soc. Am. Proc.* 46: 970-976.

- 1 Juo, A.S.R., and R.L. Fox. 1977. Phosphate sorption characteristics of some bench-mark
2 soils of west Africa. *Soil Sci.* 124: 370-376.
- 3 Kolthoff, I.M., and E.B. Sandell. 1952. Textbook of quantitative inorganic analysis. MacMillian
4 Compagny, New York.
- 5 Lascano, C.E. 1994. Personal communication. CIAT Cali Colombia.
- 6 Lascano, C.E., and J. Estrada. 1989. Long-term productivity of legume-based and pure grass
7 pastures in the eastern plains of Colombia. p. 1179-1180. *In XVI International Grassland*
8 *Congress.* Nice, France.
- 9 Lavelle, P., E. Blanchart, and A. Martin. 1993. A hierarchical model for decomposition in
10 terrestrial ecosystems: application to soils of the humid tropics. *Biotropica* 25: 130-150.
- 11 Lewis, W.M., and J.F. Saunders. 1989. Concentration and transport of dissolved and
12 suspended substances in the Orinoco River. *Biogeochem.* 7: 203-240.
- 13 Lopez-Hernandez, D. 1991. Phosphorus dynamics in a flooded savanna. p. 95-105. *In H.*
14 *Tiessen, D. Lopez-Hernandez and I.H. Salcedo (ed.) Phosphorus cycles in terrestrial and*
15 *aquatic ecosystems. Proc. Workshop SCOPE and UNEP, Maracay, 28 Nov.- 6 Dez.*
16 *1989.*
- 17 Lopez-Hernandez, D., P. Lavelle, J.C. Fardeau, and M. Nino. 1993. Phosphorus
18 transformations in two P-sorption contrasting tropical soils during transit through
19 *Pontoscolex corethrurus* (Glossoscolecidae: Oligochaeta). *Soil Biol. Biochem.* 25: 789-
20 792.
- 21 McGill, W.B., and C.V. Cole. 1981. Comparative aspects of C, N, S, and P cycling through
22 soil organic matter during pedogenesis. *Geoderma* 26: 267-286.
- 23 Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of
24 phosphate in natural waters. *Analytica Chimica Acta* 27: 31-36.
- 25 National Research Council. 1984. Nutrient requirements of beef cattle. National Academy of
26 Sciences.
- 27 Oberson, A., J.C. Fardeau, J.M. Besson, and H. Sticher. 1993. Soil phosphorus dynamics in
28 cropping systems managed according to conventional and biological agricultural
29 methods. *Biol. Fertil. Soils* 16: 111-117.
- 30 Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403-430. *In A.L. Page, R.H. Miller and*
31 *D.R. Keeney (ed.) Methods of Soil analysis, Part 2. Chemical and microbiological*

- 1 properties. ASA, and SSSA, Madison, WI.
- 2 Parton, W.J., R.L. Sanford, P.A. Sanchez, and J.W.B. Stewart. 1989. Modeling soil organic
3 matter dynamics in tropical soils. p. 153-171. *In* D.C. Coleman, J.M. Oades and G.
4 Uehara (ed.) Dynamics of soil organic matter in tropical ecosystems. NifTAL Project,
5 University of Hawaii Press, Honolulu.
- 6 Parton, W.J., J.W.B. Stewart, and C.V. Cole. 1988. Dynamics of C, N, P and S in grassland
7 soils: a model. *Biogeochem.* 5: 109-131.
- 8 Plá, I. 1988. Desarrollo de índices y modelos para el diagnóstico y prevención de la
9 degradación de suelos en Venezuela. Banco Consolidado, Caracas, Venezuela.
- 10 Rao, I.M. 1994. Unpublished results. CIAT, Cali Colombia.
- 11 Rao, I.M., M.A. Ayarza, R.J. Thomas, M.J. Fisher, J.I. Sanz, J.M. Spain, and C.E. Lascano.
12 1992. Soil-plant factors and processes affecting productivity in ley farming. p. 145-175. *In*
13 CIAT (ed.) Pastures for the tropical lowlands. CIAT Publ. 211, Cali, Colombia.
- 14 Rao, I.M., M.A. Ayarza, and R.J. Thomas. 1994. The use of carbon isotope ratios to evaluate
15 legume contribution to soil enhancement in tropical pastures. *Plant Soil* 162: 177-182.
- 16 Raveh, A., and Y. Avnimelech. 1979. Total nitrogen analysis in water, soil and plant material
17 with persulfate oxidation. *Water Res.* 13: 911-912.
- 18 Sánchez, P.A., and T.J. Logan. 1992. Myths and Science about the chemistry and fertility of
19 soils in the tropics. p. 35-46. *In* R. Lal and P.A. Sánchez (ed.). Myths and science of soils
20 of the tropics. SSSA Spec. Publ.29, SSSA Madison, WI.
- 21 Sánchez, P.A., and G. Uehara. 1980. Management considerations for acid soils with high
22 phosphorus fixation capacity. p. 471-514. *In* F.E. Khasawneh, E.C. Sample and E.J.
23 Kamprath (ed.) The role of phosphorus in agriculture. ASA, CSSA, and SSSA, Madison,
24 WI.
- 25 Sharpley, A.N. 1985. Phosphorus cycling in unfertilized and fertilized agricultural soils. *Soil*
26 *Sci. Soc. Am. J.* 49: 905-911.
- 27 Seeling, B., and R.J. Zasoski. 1993. Microbial effects in maintaining organic and inorganic
28 solution phosphorus concentrations in a grassland topsoil. *Plant Soil* 148: 277-284.
- 29 Stewart, J.W.B., and H. Tiessen. 1987. Dynamics of soil organic phosphorus. *Biogeochem.* 4:
30 41-60.

- 1 Tabatabai, M.A. 1982. Soil enzymes. p. 903-947. *In* A.L. Page, R.H. Miller and D.R. Keeney
2 (ed.) *Methods of Soil analysis, Part 2. Chemical and microbiological properties*. ASA, and
3 SSSA, Madison WI.
- 4 Tergas, L.E., O. Paladines, I. Kleinheisterkamp, and J. Velasquez. 1984. Productividad
5 animal de *Brachiaria decumbens* sola y con pastoreo complementario en Pueraria
6 phaseoloides en los Llanos Orientales de Colombia. *Producción Animal Tropical* 9: 1-13.
- 7 Thibaud, M.C., C. Morel, and J.C. Fardeau. 1988. Contribution of phosphorus issued from
8 crop residues to plant nutrition. *Soil Sci. Plant Nutr.* 34: 481-491.
- 9 Thomas, R.J. 1992. The role of the legume in the nitrogen cycle of productive and
10 sustainable pastures. *Grass Forage Sci.* 47: 133-142.
- 11 Thomas, R.J., and N.M. Asakawa. 1993. Decomposition of leaf litter from tropical forage
12 grasses and legumes. *Soil Biol. Biochem.* 25: 1351-1361.
- 13 Thomas, R.J., M.J. Fisher, M.A. Ayarza, and J.I. Sanz. 1994. The role of forage grasses and
14 legumes in maintaining the productivity of acid soils in Latin America. *Adv. Soil Sci.* (in
15 print).
- 16 Tiessen, H., I.H. Salcedo, and E.V.S.B. Sampaio. 1992. Nutrient and soil organic matter
17 dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agric. Ecosystems*
18 *Environ.* 38: 139-151.
- 19 Tiessen, H., and J.O. Moir. 1993. Characterisation of available P by sequential extraction. p.
20 75-86. *In* M.R. Carter (ed.) *Soil sampling and methods of analysis*. CRC Press, Boca
21 Raton, FL.
- 22 Tiessen, H., J.W.B. Stewart, and J.O. Moir. 1983. Changes in organic and inorganic
23 phosphorus composition of two grassland soils and their particle size fractions during 60-
24 90 years of cultivation. *J. Soil Sci.* 34: 815-823.
- 25 Tiessen, H., J.W.B. Stewart, and A. Oberson. 1994. Innovative phosphorus availability
26 indices: assessing organic phosphorus. *In* SSSA (ed.) *Soil testing: Prospects for*
27 *improving nutrient recommendations*, SSSA Spec. Publ. 40 (in print).
- 28 Umrit, G., and D.K. Friesen. 1994. The effect of C:P ratio of plant residues added to soils of
29 contrasting phosphate sorption capacities on P uptake by *Panicum maximum* (Jacq.).
30 *Plant Soil* 158: 275-285.
- 31 von Uexküll, H.R., and E. Mutert. 1993. Global extent, development and economic impact of

- 1 acid soils. Proc. 3rd Symposium on plant-soil interactions at low pH, Brisbane, 12-16
2 Sept. 1993.
- 3 Williams, J.D.H., T. Mayer, and J.O. Nriagu. 1980. Extractability of phosphorus from
4 phosphate minerals common in soils and sediments. Soil Sci. Soc. Am. J. 44: 462-465.
- 5 Williams, J.D.H., J.K. Syers, R.F. Harris, and D.E. Armstrong. 1971. Fractionation of inorganic
6 phosphate in calcareous lake sediments. Soil Sci. Soc. Am. Proc. 35: 250-255.

Table 1. pH and exchangeable cations in the 0-10 cm soil layer of native savanna (SA) and improved pastures (grass-only (GO) and grass-legume (GL)).

	pH	Al	Ca	Mg	K	H
	cmol kg ⁻¹					
Mean SA	4.8 b	2.42 a	0.26 b	0.11 b	0.08	0.27 b
SE†	0.03	0.04	0.02	0.01	0.00	0.01
Mean GO	4.9 b	2.05 b	0.42 b	0.20 a	0.10	0.39 a
SE†	0.03	0.06	0.03	0.02	0.00	0.02
Mean GL	5.0 a	1.90 b	0.89 a	0.23 a	0.09	0.26 b
SE†	0.03	0.07	0.07	0.01	0.00	0.00
F-Test‡	**	***	***	***	NS	***

† Mean and standard error of mean (SE) of 8 samples per treatment. Means followed by the same letter are not significantly different ($P=0.05$) by Tukey's multiple range test.

‡ F-Test: *** $P<0.001$, ** $P=0.001-0.0$, * $P=0.01-0.05$.

Table 2. Fertilizer input over 15 years (1978-1993) in the long term pastures.

Treatment	N	P	K	Ca	Mg	S
	kg ha ⁻¹					
GO	0	103	63	648	56	77
GL	0	106	80	648	63	90

Table 3. Inorganic and organic P fractions in the 0-10 cm soil layer in native savanna and improved pastures.

	Resin-P _i	H ₂ O-P _o	Bic-P _i	Bic-P _o	NaOH-P _i	NaOH-P _o	HCl-P _i	HCl _{hc} -P _i	HCl _{hc} -P _o	Resid-P _t	SumPT‡	Extr. P _o §	PT¶	Bray II
	mg P kg ⁻¹													
mean SA	3.5 b	2.7 b	3.3 b	9.6	23.1 b	43.1 b	1.3	54.1 b	8.3	50.9 ab	200 b	63.8 b	185 b	1.3 b
SE†	0.2	0.1	0.1	0.7	0.7	1.8	0.1	1.6	1.9	1.4	2	2.6	3	0.1
Sum %	1.7	1.4	1.7	4.8	11.6	21.6	0.6	27.1	4.2	25.4	100	31.9	92.3	
mean GO	4.0 b	4.3 a	3.4 b	9.9	22.8 b	41.4 b	1.8	60.6 b	12.7	49.9 b	211 b	68.4 ab	193 b	1.4 b
SE†	0.1	0.5	0.1	0.6	0.8	2.1	0.3	3.1	2.6	1.1	8	3.6	6	0.2
Sum %	1.9	2.1	1.6	4.7	10.8	19.6	0.9	28.8	6.0	23.6	100	32.3	91.5	
mean GL	5.2 a	3.5 ab	4.6 a	9.6	31.1 a	51.9 a	1.5	68.6 a	12.1	54.9 a	240 a	77.1 a	227 a	2.2 a
SE†	0.4	0.3	0.2	0.5	1.2	3.1	0.1	1.5	2.5	0.9	6	3.8	5	0.3
Sum %	2.2	1.5	1.9	4.0	13.0	21.7	0.6	28.6	5.0	22.9	100	31.2	93.9	
F-Test	***	*	***	NS	***	**	NS	***	NS	*	***	*	***	**

† Mean and SE for 8 (GO and SA) and 7 (GL) samples per treatment. Other statistical indications: see table 1.

‡ Sum of all fractions.

§ Sum of extracted organic P fractions.

¶ Total P determined by perchloric acid digest.

Table 4. Estimated P budget over 15 years (1978-1993) in native savanna and improved pastures, and comparison with measured total P (PT) increases due to fertilization.

Treatment	Estimated P budget			Measured PT difference †	Balance unaccounted for
	Input	Export	Balance		
kg P ha ⁻¹					
SA	-	2.1	-2.1		
GO	103	24	+79	10.4	70.7
GL	106	36	+70	54.6	17.5

† Difference in PT content (10 cm soil depth; from table 3) between improved pastures and native savanna.

Table 5. C content in different extractants of the sequential P fractionation procedure.

	H ₂ O-C	Bic-C	NaOH-C	HCl _{hc} -C	Extr.C§	Resid-C	CT¶
	mg C g ⁻¹						
mean SA	0.6	1.8	8.7	3.3 b	14.4	9.1	23.5 ab
SE†	0.1	0.1	0.3	0.1	0.4	0.5	0.7
CT%#	2.6	7.7	37.0	14.0	61.3	38.7	100.0
mean GO	0.9	1.8	8.4	3.2 b	14.3	8.9	23.2 b
SE†	0.1	0.0	0.3	0.1	0.3	0.5	0.5
CT%#	3.9	7.8	36.2	13.8	61.6	38.4	100.0
mean GL	0.9	2.0	8.9	3.5 a	15.4	9.5	24.9 a
SE†	0.1	0.1	0.2	0.1	0.3	0.2	0.4
CT%#	3.6	8.0	35.7	14.0	61.8	38.2	100.0
F-Test	*‡	NS	NS	**	*‡	NS	*

† Mean and SE for 8 (GO and SA) and 7 (GL) samples per treatment. Other statistical indications: see table 1.

‡ Tukey test not significant.

§ Sum of C in extracted fractions.

¶ Total C determined with combustion in a LECO CR-12 furnace with infrared detection of CO₂.

% of Total C.

Table 6. N content in different extractants of the sequential P fractionation procedure.

	H ₂ O-N	Bic-N	NaOH-N	HCl _{HC} -N	Extr.N‡	Resid-N	SumNT§	NT¶
mg N kg ⁻¹								
mean SA	37.1 b	287	537 b	342 b	1203 b	329 b	1533 b	1454 b
SE†	3.8	9	11	15	31	11	28	28
SNT%#	2.4	18.7	35.0	22.3	78.5	21.5	100	94.8
mean GO	68.2 a	282	541 b	367 ab	1258 ab	291 c	1549 b	1555 b
SE†	11.1	3	9	11	23	8	29	24
SNT%#	4.4	18.2	35.0	23.7	81.2	18.8	100	100.3
mean GL	54.0 ab	304	591 a	409 a	1358 a	369 a	1727 a	1670 a
SE†	7.0	9	11	26	37	9	42	41
SNT%#	3.1	17.6	34.2	23.7	78.6	21.3	100	96.7
F-Test	*	NS	**	*	**	***	***	***

† Mean and SE for 8 (GO and SA) and 7 (GL) samples per treatment. Other statistical indications: see table 1.

‡ Sum of N in extracted fractions.

§ Sum of Extr.N and Resid-N.

¶ Total N determined by Kjeldahl method.

% of SumNT.

Table 7. C/N, C/P_o and N/P_o ratios in different extracts of the sequential fractionation procedure as well as C/N/P_o for N = 10. Geometric means over all field treatments.

	H ₂ O	Bic	NaOH	HCl _{hc}	Extr†	Resid‡	Total§
C/N	16.0	6.5	16	9.0	11.5	28	14
C/P _o	229	197	192	354	212	176	345
N/P _o	14	33	12.4	39	18.4	6.3	20
C/N/ P _o	160/10/ 0.71	65/10/ 0.33	160/10/ 0.80	90/10/ 0.26	115/10/ 0.54	280/10/ 1.6	137/10/ 0.51

† Ratio between sum of extracted C, N and P_o, respectively.

‡ Ratio between Resid-C, Resid-N and Resid-P_t.

§ Ratio between total C, total N and the sum of extracted organic P.