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Nutrient and mercury variations in soils from family farms of the Tapajós region (Brazilian Amazon): Recommendations for better farming

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Abstract

In the Brazilian Amazon, colonization is modifying the landscape at an exceedingly fast pace. Recently established households practice slash-and-burn agriculture and participate in the overall deforestation of the Amazon. Near the Transamazon highway, these family agricultural practices are the main cause of deforestation. The study presented here is oriented toward a better understanding of the impacts of farming practices on soil chemical composition. This study used a sampling design based on soil samples taken on farm plots, which had been submitted to a wide range of spatial and temporal sequential land-uses, including soils that were only recently denuded. The data shows that soil responses (organic matter (OM) content, fertility and mercury (Hg) retention) to these varied land-uses were relatively similar, suggesting that the most important event determining the responses was deforestation itself. This is well illustrated by the Hg content of soils, which changed immediately after deforestation and then only slightly thereafter. This phenomenon could also be seen in the base cation (calcium (Ca), potassium (K) and magnesium (Mg)) content which rose drastically after deforestation and tended to stay high for a period up to 10 years of cropping and pasture. This lasting cation rise is reflected by ammonium (NH_4) displacement from surface soils. Indeed, inorganic nitrogen (N) is the most important nutrient loss upon deforestation. Nonetheless, when time spent in fallow was greater than 15 years, base cations (Ca, Mg, K), available N and phosphorus (P) contents tended to go back to initial forest soil values and in some cases to exceed them. Soil type was seen to mediate responses to land-use. Clay-sandy soils showed a lower content of available N and carbon (C) than clayey soils at the soil surface, a difference that was accentuated by deforestation. Conversely, the higher initial content of Hg in clayey soils was associated with a more important Hg loss from the soil's surface. By shedding light on the consequences of family practices for OM, nutrient status and Hg depletion, this paper gives a new perspective on soil responses to agricultural practices. These conclusions need to be addressed in a strategy plan to limit family land-use impacts on soils and the surrounding ecosystems. Recommendations for more sustainable land uses are proposed based on what has been learned about soil responses to local agricultural practices.

Keywords: Deforestation; Amazon; Agriculture; Land use; Mercury; Cations; Phosphorus; Nitrogen

1. Introduction

In the face of rapid deforestation of the Amazon, growing concerns call for actions to protect this unique mosaic of ecosystems. From a conservationist point of view, no reason may be valuable enough to allow for the destruction of the most diversified terrestrial ecosystem of the planet. However, many reasons incite local people to explore

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different land-uses of the Amazon region. Economic incentives are the principal argument put forward in the debate and deforestation benefits many actors, from the government to timber companies, from large landowners to family farmers (Walker et al., 1997; Margulis, 2004). Depending on the Amazon region considered, deforestation for agricultural purposes may be for large-scale activities such as soy plantations and pastures or for subsistence farming. Family farming is widespread all over the Amazon, some regions being rapidly deforested as a result. In Rondônia state, for example, practically all land clearing is carried out by small-scale cultivators (Calviglia-Harris, 2003). Family farming is also the leading cause of deforestation, ahead of large-scale pastures and tree harvesting, in the study region of this research, which is located in the State of Pará near the TransAmazon highway. Sustainable agriculture is often proposed as a solution to limit slash-and-burn practices. However, proposed solutions have to be adapted to local communities, taking into account their cultural, economic and environmental characteristics.

This study was part of a broader research project, which aims at better understanding family agriculture in a recently colonized region. Deforestation is destabilizing the entire ecosystem and among other impacts, it has been suggested that Hg is leached from soils, possibly contributing to aquatic ecosystem contamination (Farella et al., 2001; Roulet et al., 1998). Since fish Hg contamination poses a threat to human health (Lebel et al., 1998), addressing the environmental Hg cycle is crucial. This research project considered changes in farming practices to lower Hg contamination, to protect soil and forest resources, and to ensure a long-term land occupation for concerned populations. Sociological, economic and geographic aspects were studied and gave a comprehensive portrait of subsistence farming near the TransAmazon highway (Farella, 2005). The specific focus of this paper was to analyze changes in fertility and Hg retention in soils submitted to family farming practices through a combination of measurements: OM, cations, N, P and Hg. Most studies on the responses of soils submitted to varied land-uses in the Amazon propose a comparative analysis of these land-uses on sites with a singular land-use since deforestation (e.g. Cerri et al., 1991; Holscher et al., 1997; Sanchez et al., 1983; Garcia-Montiel et al., 2000). However, these studies do not take into account the complexity and diversity of land-uses on family farms. The present study aimed to address this knowledge gap by including sites that were representative of actual family land-uses. Samples were situated on sites presenting a variety of historical uses such as numerous cycles of crops and fallows. With a representative sampling of household land, this study allowed us to get a more precise perspective on soil responses to farming practices. The use of medians while treating thousands of data points circumvents problems inherent to soil heterogeneity and gives an accurate portrait of soil response to land use. Ultimately, the objective of this paper is to propose strategies for the elaboration of better farming practices for the Tapajós region and similar regions of the humid tropics, based on measured soil responses of family farming.

2. Methods

2.1. Research area

The present study took place in a remote region of the Brazilian Amazon, a few tens of km from the TransAmazon highway. The nearest city is Itaituba, situated some 60-km southwest of the study region along the Tapajós River. The entire region around Itaituba is an active colonization front. Moreover, the state of Pará is one of the three Amazonian states in which 85% of total Brazilian Amazonian deforestation occurs (Margulis, 2004). The TransAmazon Highway acts as a catalyst for deforestation: Chomitz and Thomas (2000) estimate that 85% of deforestation occurs in a perimeter of 50 km from roads. In the state of Pará, the annual deforestation rate was appraised at 8200 km^2 in 2002–2003 (INPE, 2004). The specific study region was located near the village of Brasília Legal, on the opposite bank of the Tapajós River, an important affluent of the Amazon River. The sampling area was chosen based on collective research needs. Sampling was conducted on family agricultural lands situated within a few km each other. All of the sampling sites were located on the banks of three lakes belonging to the Tapajós floodplain: Lago Pereira, Lago Cupu and Lago Bom Intento. When questioned, people mentioned living in that area from less than 1 year up to 37 years (Farella, 2005). The median time since settlement was 14 years (Farella, 2005). The principal land-use in this region was the cultivation of temporary crops (manioc: *Manihot esculenta* Crantz, rice: *Oryza sativa* L., bananas: *Musa* spp. and beans: *Phaseolus vulgaris* L.) interrupted with fallow, and generally ending with pasture. Apart from these cultivation sequences, small areas were dedicated to fruit tree plantations, a marginal land-use. Forest still covered approximately 55% of family land, but forested areas were lost to newly cultivated plots each year (Farella, 2005).

2.2. Sampling and analyses

Soil sampling was conducted with the collaboration of local people. Sampling was pursued only on sites where individuals could recount the history of land-use, in order to ensure reliability of past land-use. At the time of sampling, the precise historical background of land-use was asked to informants, including the number of years of cultivation, the number of fires, the number of years of fallow, etc. For each site, a complete chronology of events was constructed. For most sites, respondents were able to provide a fairly complete history of land use. In some cases however, doubts remained on the total number of years spent in crop or fallow. Generally, these cases concerned some sites that were deforested by a former landowner. They were left in the data set because they represented older sites. Verification of the history of sites was made with the informants, which contributed to reducing errors. Time spent in crop, fallow and pasture were calculated for each site. This characterization allowed us to compare sites with very different histories. For example, time spent in pasture may also include some years spent in crops or in fallow, and time spent in crop may also include time spent in fallow. This sampling design is very innovative as it represents the actual land-use.

A total of 25 family farms were sampled, representing one hundred different sites. At each site, three different cores were sampled with a percussion sampler, approximately 10 m apart. The first 5 cm under the leaf litter was considered as representative of the soil surface, while the 20–25 cm horizon and the 50–55 cm horizon were sampled to evaluate sub-soil surface pedological dynamics. Prior to any chemical analysis, samples were passed through a 2-mm mesh, lyophilized and finally homogenized in a stainless steel grinder. Several physico-chemical variables were determined. Hg was extracted with HCl and measured by atomic fluorescence (Pichet et al., 1999). Cations (Ca, Mg, K) were extracted with $BaCl_2$ and measured by atomic absorption (Hendershot et al., 1993). Mineral N (NO_3 and NH_4) was extracted with KCl 2 M (Maynard and Kalra, 1993) and analyzed by colorimetry (auto-analyzer TRAACS 800). Total C and N were measured on Carlo-Erba NA-1500 analyzer. Oxy-hydroxides of Fe and Al were extracted using the citrate–dithionate–bicarbonate (cdb) buffer method (Lucotte and d'Anglejan, 1985), and analyzed by atomic absorption. The different P compounds (orthophosphate and organic) were isolated following a sequential extraction and measured by colorimetry (auto-analyzer TRAACS 800) (Lucotte and d'Anglejan, 1985). The abbreviations Fe-cdb, Al-cdb, P-cdb and P-org are used to qualify these different chemical fractions.

Since the soils sampled displayed a wide variety of colour and texture, soils were categorized in order to minimize differences essentially due to the inherent heterogeneity of soil types. Two approaches were tested to propose a valid soil discrimination model. First, a colour characterization based on the Munsell chart was made for each dry soil sample. Colours showed a wide gradient of tones from grayish yellow to brownish red. This significant heterogeneity of soil colours prevented grouping, hence, a second method, based on fine particle content (FP), was chosen to distinguish soil categories. Granulometric fractions were weighed after humid fractionation and soil groups were separated following their content of fine particles, defined as smaller than 63 μm. Fine particle content is recognized to play an important role in tropical soil chemical properties (Botschek et al., 1996; Bernoux et al., 1998). A factorial analysis including all sites and their corresponding percentile of FP showed that a threshold of 65% FP allowed for the differentiation of our soil sample pool into two distinct groups. The soil group with less than 65% FP corresponded to paler brown-yellowish soils, possibly related to the group of Ultisols according to the USDA classification (or Acrisols for FAO/UNESCO). The soil group characterized by more than 65% FP included mainly darker brown-yellowish soils and is possibly related to the Oxisols of the USDA classification (or Ferralsols for FAO/UNESCO). We will use the terminology clay-sandy soils (<65% FP) and clayey soils (>65% FP) to label these two soil groups throughout the present article.

2.3. Soil data set presentation

Most studies illustrating the impacts of land-use through time on the soils of the Amazon region are based on the analysis of a few sites and compare forested sites to sites submitted to one land-use over a certain period of time. In this study a different approach was used, based on a broad sampling which allowed us to explore the impacts of non-linear land-use on soils over a period of a quarter of a century. The soil-sampling program was pursued on the agricultural land of 25 households. Each site had a different historical record; some being deforested for less than a year while others went through many subsequent cycles of crop and fallow. To consider this complex historical land use, thus allowing to compare all sites together, we propose an innovative approach. Time spent in crop, fallow and pasture were summed for each site. Figs. 1–10 feature median values of soil variables (at surface and at 50 cm depth) in relation to the time spent in a particular land-use. The use of medians proved to be more stable and accurate than means because of the skewed distribution of data and the heterogeneity in soil types. The graphs using medians display clear trends that allow for reasonable interpretations. Nine chemical soil variables are presented in this paper. Twenty other variables were also measured and principal component analysis were performed on these data (see Farella et al., 2006). Table 1 shows the time frame categories established for the soil data set which were used to build the figures, in relation to the three land-uses (pasture, crop and fallow) and the two soil types (clay-sandy and clayey). These categories were determined in order to obtain a sufficient sample size for each ($n > 9$ in general) and to be as balanced as possible within each category. Categories were also determined in such a way as to obtain comparable time frames between the two soil types. In each time frame category, the median value was chosen to represent this time interval on the *x*-axis. For instance, a value of 2.5 years was used to represent the time frame category 1–4 years. The values on the *y*-axis correspond to the median value of all samples within this time interval. This methodology allowed for a clear graphic presentation of the soil data given the naturally high soil heterogeneity. Median soil values were compared to a baseline that corresponds to the unperturbed forested sites. Twenty-seven and 15 samples from forest sites were used for clay-sandy soils and clayey soils, respectively.

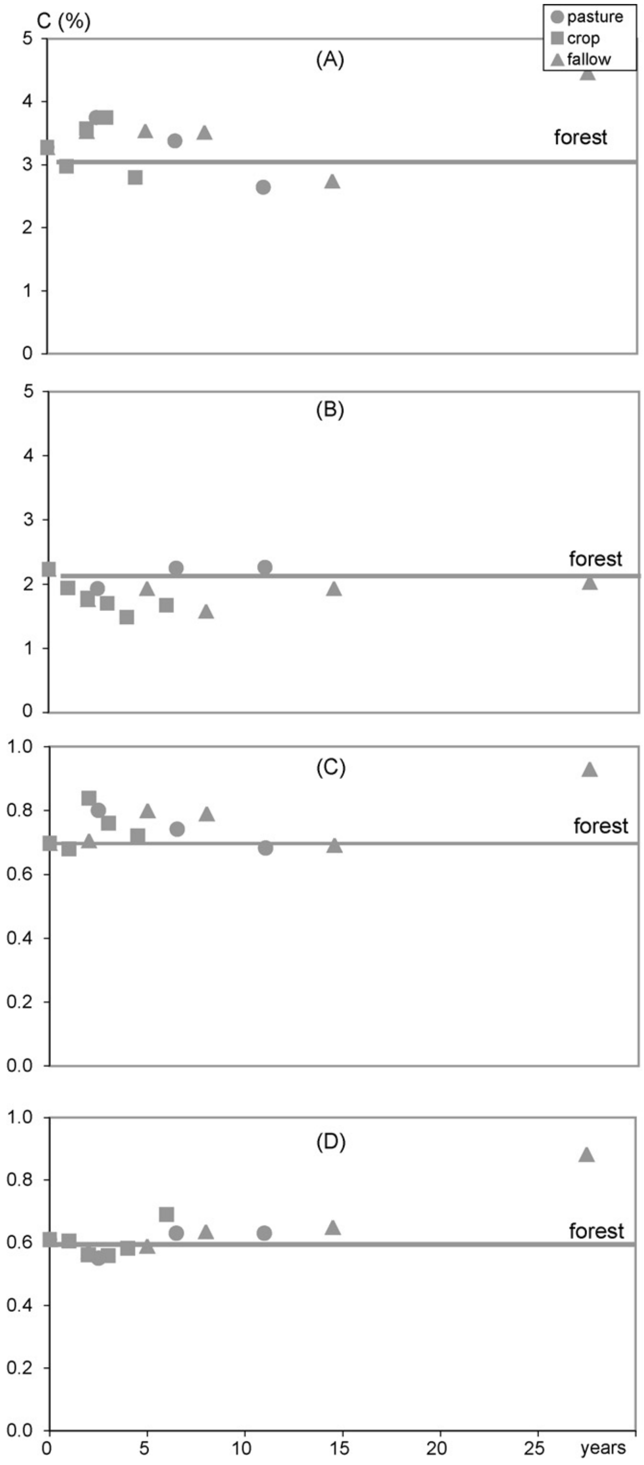

Fig. 1. C content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

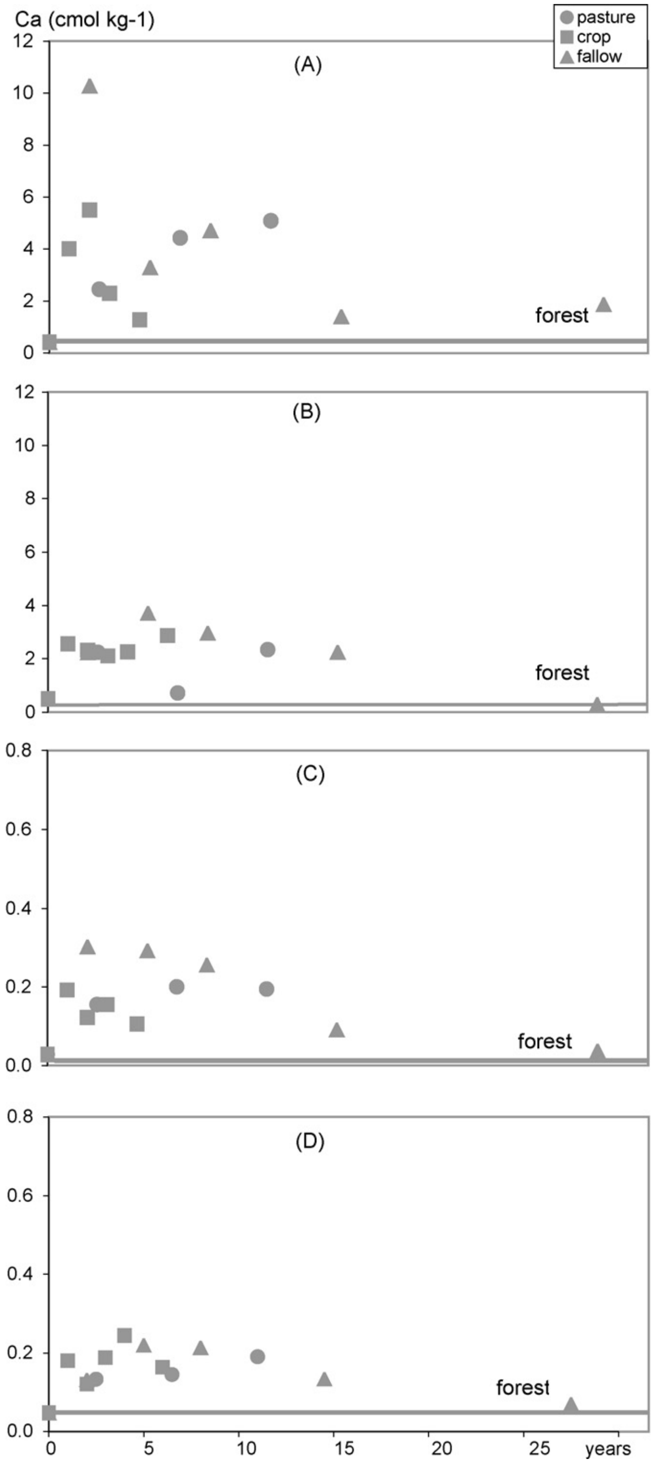

Fig. 2. Ca content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

3. Results

3.1. C content variation in soil

The C content trend was specific for each soil type (Fig. 1). For clayey soils, nearly all median-values of soils submitted to a land-use showed a C content superior to the median of forested soils. At the surface, C content went from 3.3% up to 3.8% while at deeper levels it went from 0.7% to around 0.8%. However, this increase tended to slow after a certain amount of time spent under cultivation: after 5 years in crop and 10 years in pasture or fallow, C content in clayey soils tended to

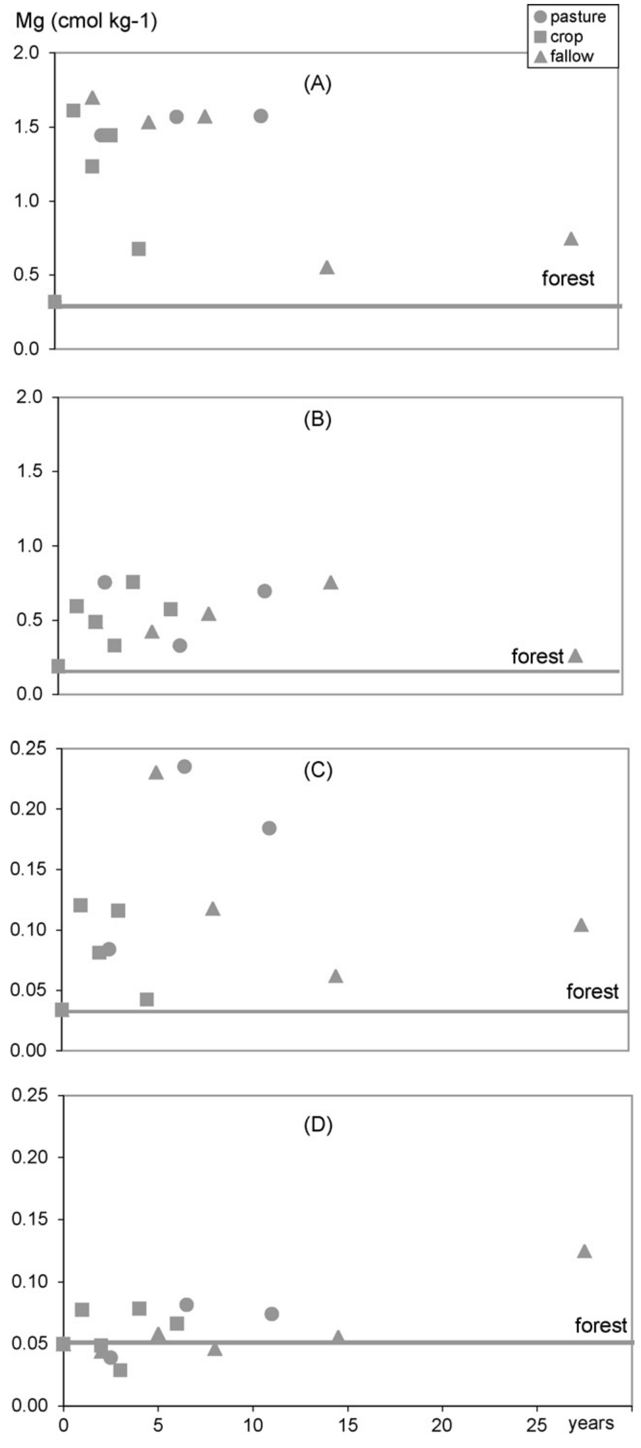

Fig. 3. Mg content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

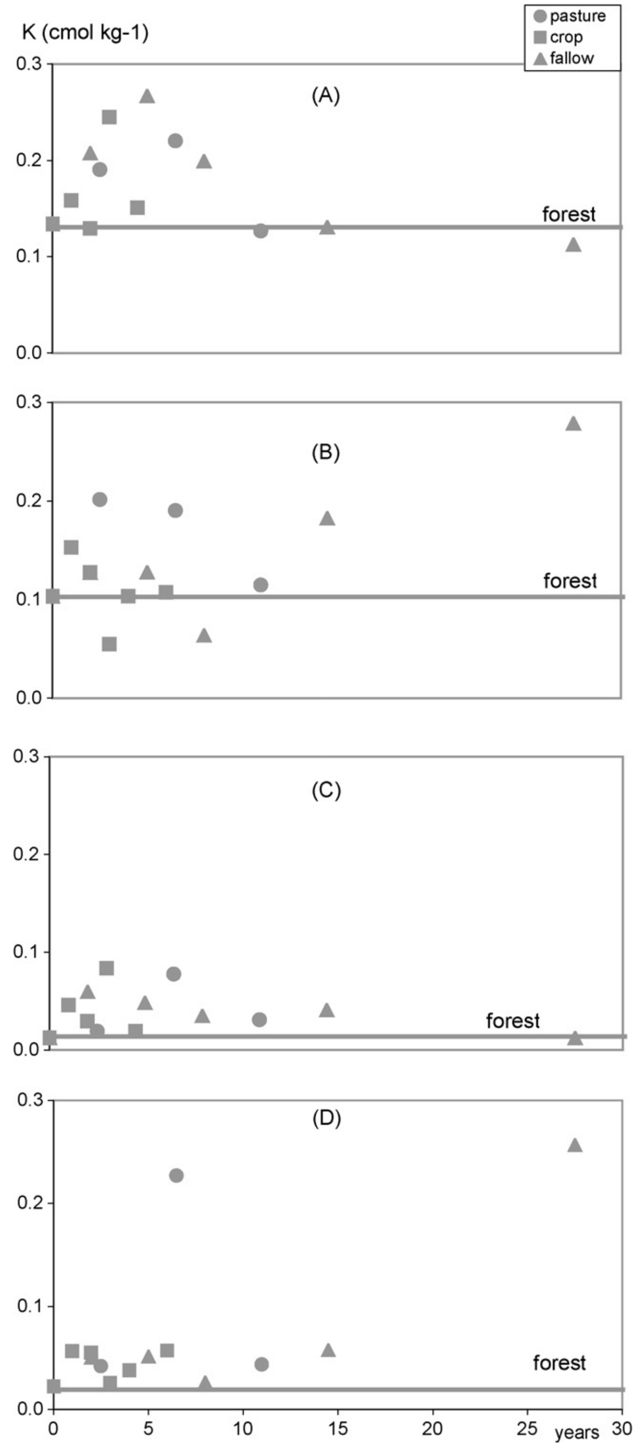

Fig. 4. K content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

fall back to initial values. C content increased again with time spent in fallow, showing an important C enrichment beyond 15 years. For clay-sandy soils, the picture was quite different: there was a clear depletion of surface C content which was more marked with time spent in crop than with time spent in pasture. Indeed, C content dropped from 2.3% in forested soils to 1.7% or less after soils had been cultivated for 3 years or more. In the deepest layers, C content was similar in forested soils and in soils submitted to any of the three land-uses, although there was a slight tendency for enrichment especially in old fallows. However, a land use superior to 5 years seemed to contribute for C enrichment in both soil horizons.

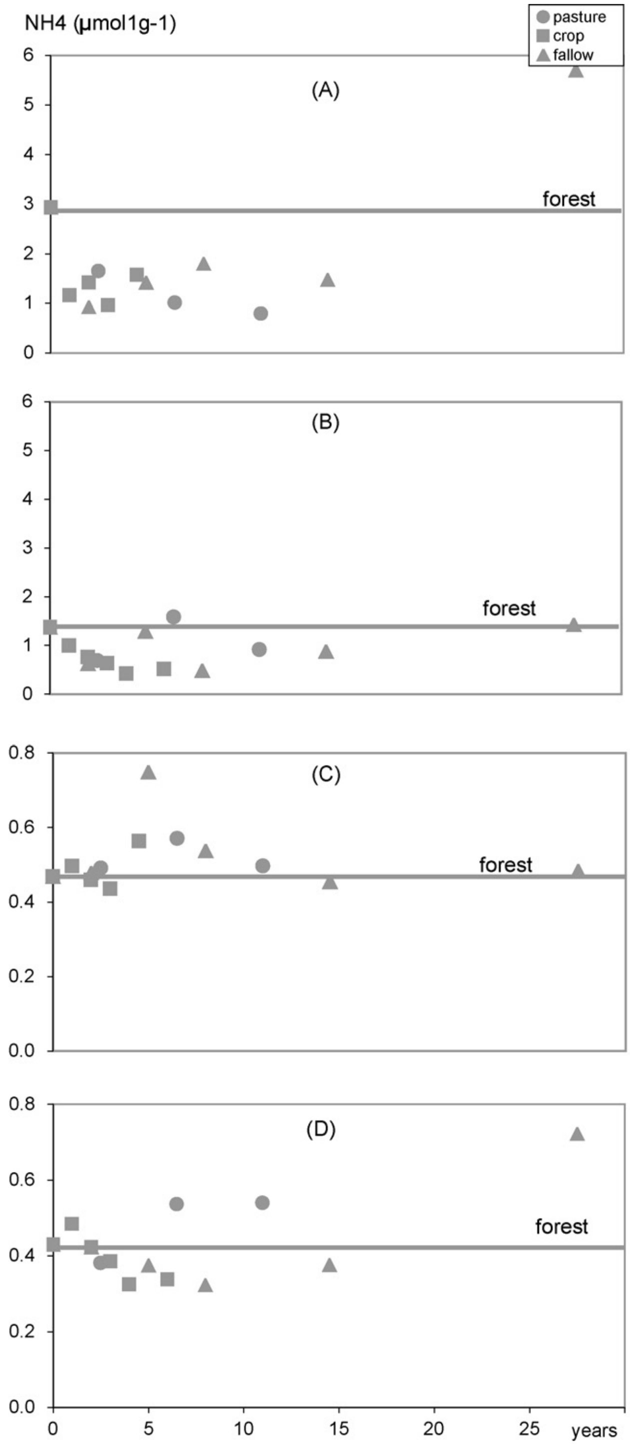

Fig. 5. NH_4 content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

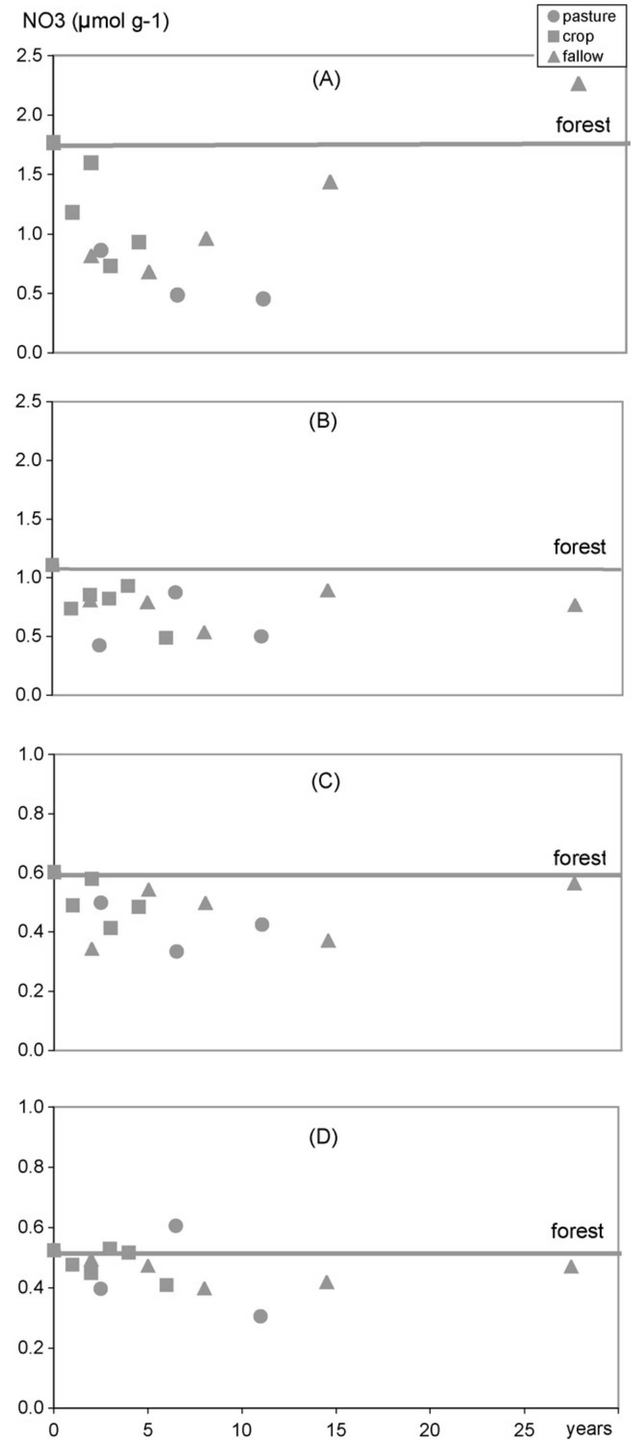

Fig. 6. NO_3 content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

3.2. Base cations content variation in soil

Ca, Mg and K (hereafter refered to as ‘‘base cations’’) showed a significant increase with duration of land-use (Figs. 2–4). Surface soils tended to experience a greater enrichment than deeper soils. Of the three base cations, Ca increased the most, followed by Mg and then K. In absolute values, all three cations increased at the surface of clayey soils: the Ca content of forested clayey soils was only 0.2 cmol kg^{-1} but reached 2–5 cmol kg^{-1} when submitted to any of the three land-uses (Fig. 2); Mg started at 0.3 cmol kg^{-1} in forested clayey soils and reached more

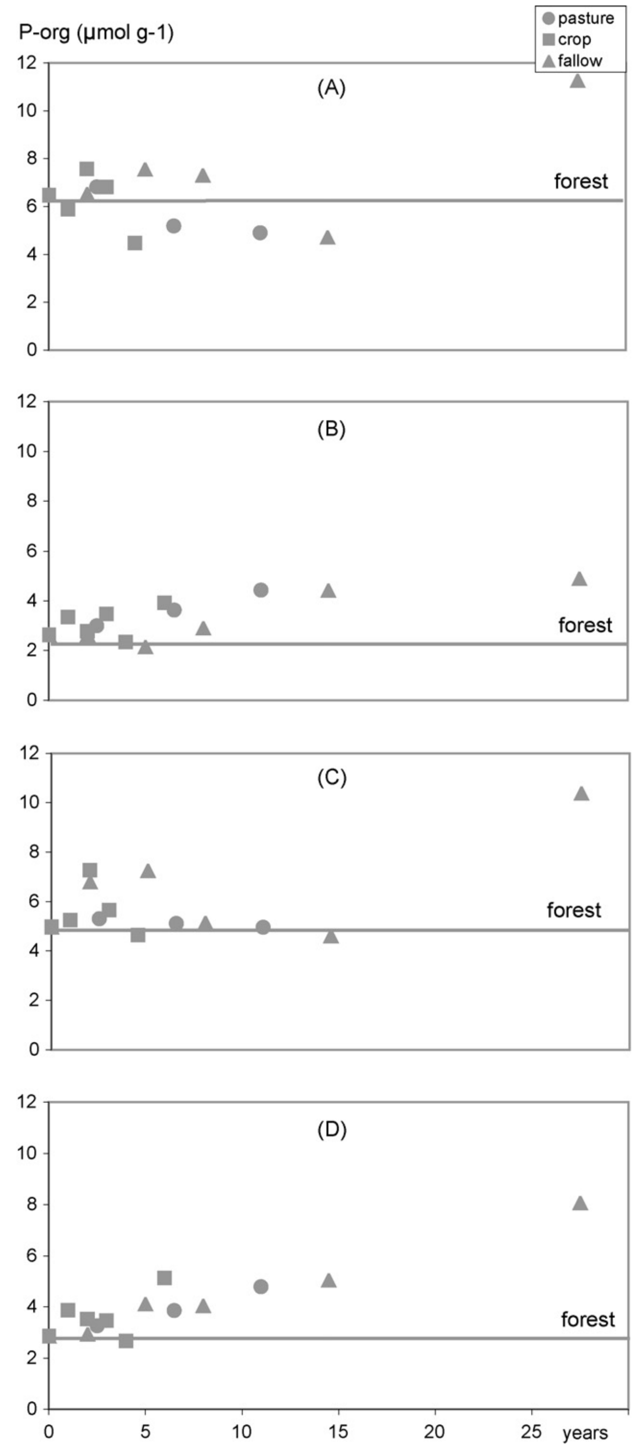

Fig. 7. P-org content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

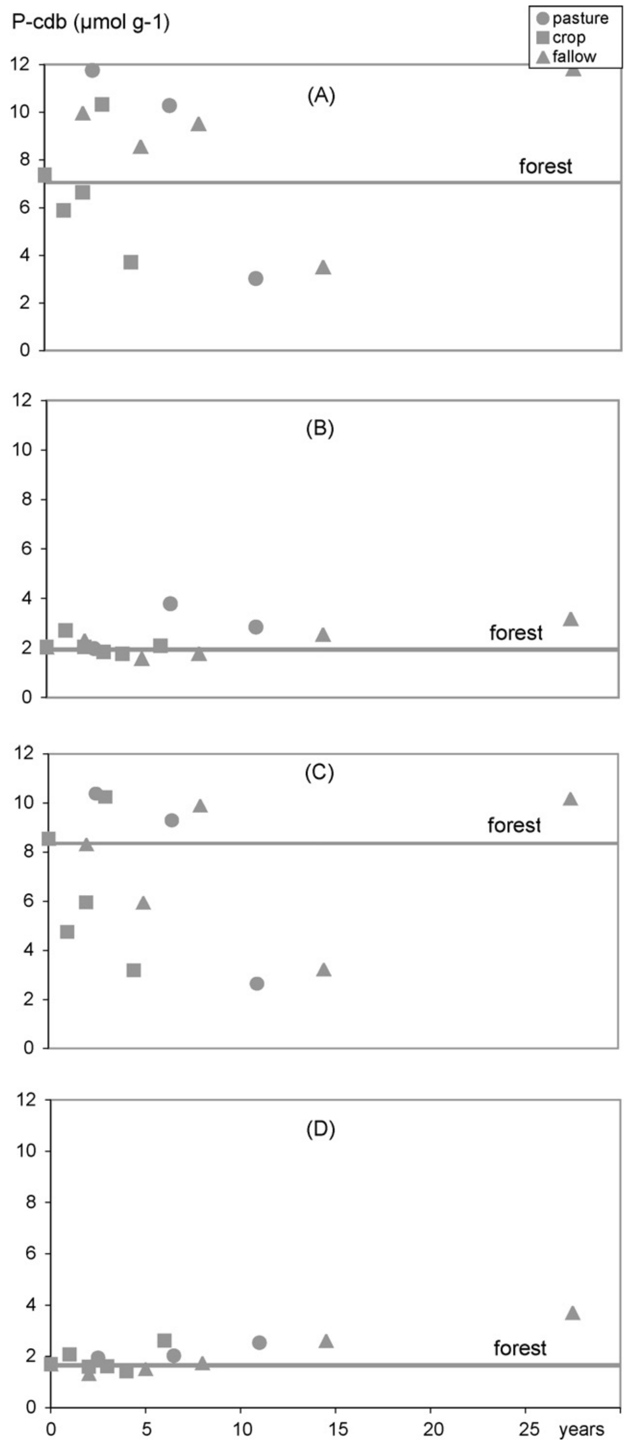

Fig. 8. P-cdb content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

than 1.5 cmol kg^{-1} through land-use (Fig. 3) and K went from 0.11 cmol kg^{-1} in forested clayey soils to over 0.20 cmol kg^{-1} with land-use (Fig. 4). Base cation content tended to be correlated with time spent in fallow. Ca content tended to fall back to forested values after 15 years or more of fallow. This trend was observed both at the surface and in deeper levels of both soil types. The same could also be said of Mg and K content in clayey soils, but generally not in clay-sandy soils where only Mg tended to return to forest values at the top layer. In pastures, base cation content tended to stay enriched even after 10 years of land-use with the only exception of K content which decreased. As for

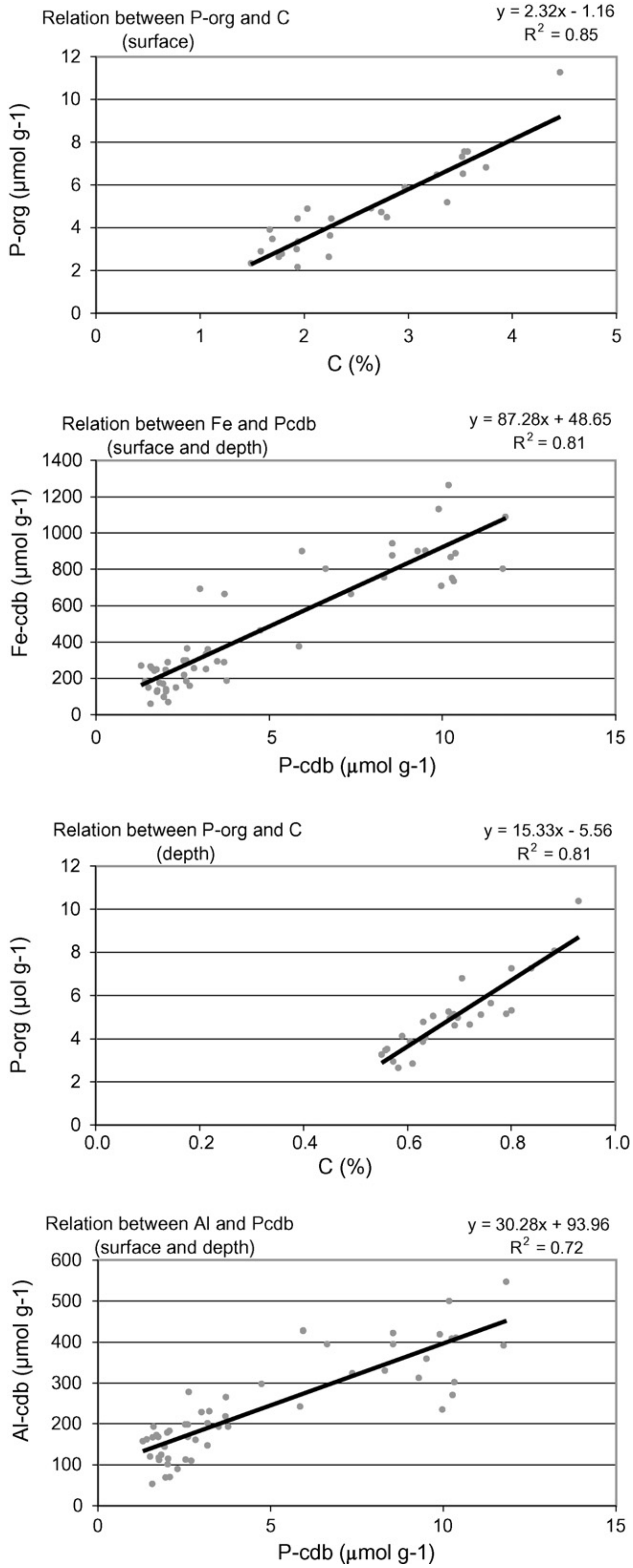

Fig. 9. Relationships between P-cdb and Fe, Al-cdb, and between P-org and C in soil under pasture, crop and fallow.

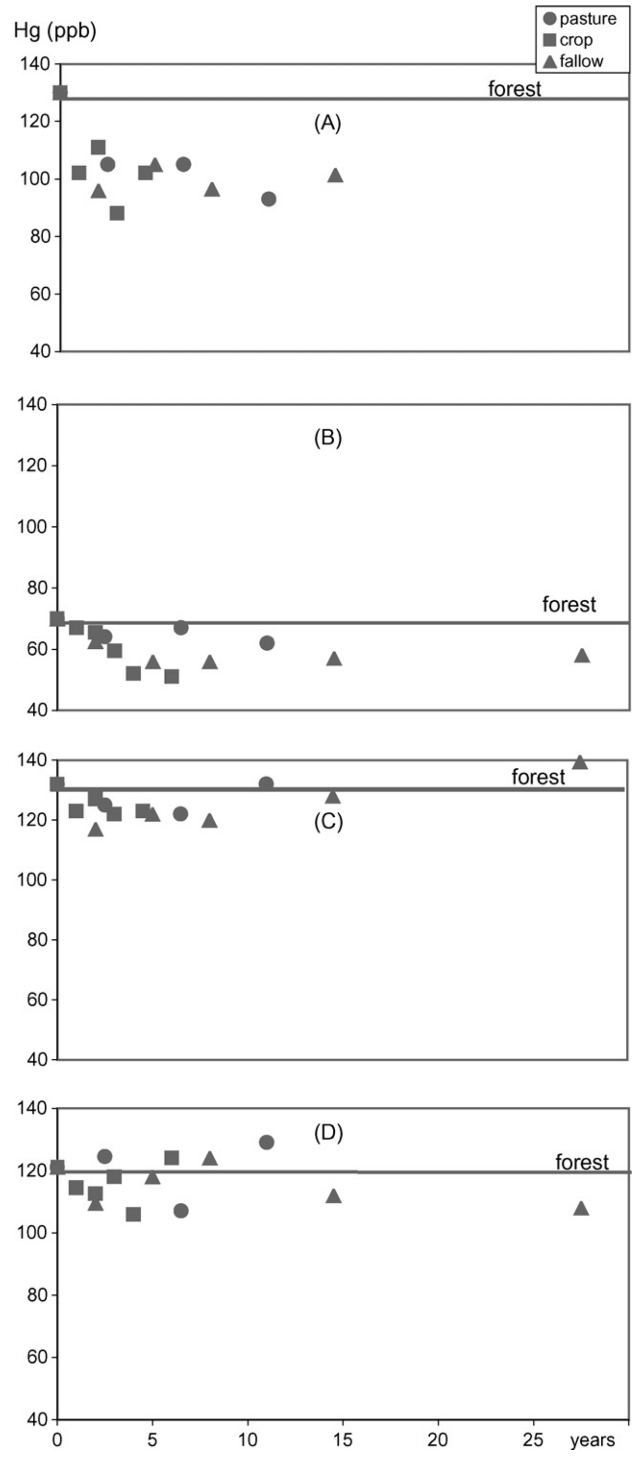

Fig. 10. Hg content in soil in relation with years of pasture, crop and fallow. (A) Surface of clayey soil; (B) surface of clay-sandy soil; (C) depth of clayey soil; (D) depth of clay-sandy soil.

crops established on clayey soils, all base cations decreased rapidly during the first 5 years spent in crop. There was no such clear trend for clay-sandy soils: Ca and Mg content tended to stay above forested values even after 5 years in crop, while K content returned to pre-perturbation values at the surface.

Table 1
Classification of the soil data set in relation to time frame categories for graph design

Clay-sandy soils			Clayey soils		
Time frame categories (years)	Median time in land-use (years)	No. of samples (n)	Time frame categories (years)	Median time in land-use (years)	No. of samples (n)
Time spent in pasture[a]					
1–4	2.5	18	1–4	2.5	15
5–8	6.5	15	5–8	6.5	12
9–13	11	9	9–13	11	9
Time spent in crop[a]					
1	1	48	1	1	36
2	2	54	2	2	21
3	3	12	3	3	15
4	4	9	4–5	4.5	9
5–7	6	9			
Time spent in fallow[a]					
1–3	2	36	1–3	2	12
4–6	5	15	4–6	5	9
7–9	8	21	7–9	8	24
10–19	14.5	15	10–19	14.5	12
20–35	27.5	6	20–35	27.5	9

[a] Soils that supported pasture, crop and fallow were grouped according to the time spent in each specific land-use. In each time frame category, the median value was chosen to represent this time interval on the x-axis. For instance, a value of 2.5 years was used to represent the time frame category 1–4 years. In the figures, the median content for the chemical variable stands for these time frame categories.

3.3. N content variation in soils

Available N (NH_4 and NO_3) was the most significantly diminished nutrient in all land uses. NH_4 and nitrate (NO_3) content of forest soils were nearly always superior to deforested soils (Figs. 5 and 6). NH_4 depletion was more marked than NO_3 depletion. Time spent in fallow, pasture and crop could cause a three-fold loss of NH_4 from surface soils, dropping from 3 μmol g^{-1} in the clayey soils of forests to values between 0.8 and 1.8 μmol g^{-1} for different land-uses and from 1.4 μmol g^{-1} in clay-sandy forest soils to values between 0.4 and 1.0 μmol g^{-1} under cultivation (Fig. 5). NO_3 depletion was most marked at the surface, especially for clayey soils, but could also be observed at deeper layers for clayey soils (Fig. 6). In deeper layers of cultivated land, NO_3 and NH_4 levels tended to equal and sometimes even exceed forest soil values. NH_4 retention is observed in deeper horizon, which is more important in clayey soils than in clay-sandy soils. Differences between land-uses were not striking; however, some particularities should be highlighted. First, NO_3 and NH_4 depletion was noted after only 1 year of cultivation, suggesting that this impact occurs rapidly after deforestation. Nonetheless, after 15 years of fallow, NO_3 and NH_4 content tended to go back to values found in forest soils.

3.4. P content variation in soil

Of both P forms presented in this study, only organic P (P-org) showed a clear response to land-use. A distinct P-org enrichment was observed for clay-sandy soils: the median content of forest soils went from 3 μmol g^{-1} at both the surface and deeper layers to 5 μmol g^{-1} after some time spent in crop, pasture or fallow (Fig. 7). For clayey soils, median forest soil values were higher and an increase was only observed in sub-surface layers where P-org content went from 5 μmol g^{-1} up to 7 μmol g^{-1} (Fig. 7). In both types of soil, maximum values were attained beyond 15 years of fallow. Contrary to P-org, orthophosphate (P-cdb) content in soils did not seem to be clearly influenced by land-use (Fig. 8). In terms of absolute content, clayey soils showed median concentrations four times greater than clay-sandy soils (8 μmol g^{-1} compared to 2 μmol g^{-1}). Moreover, median values varied much more for clayey soils, ranging from 2 μmol g^{-1} to 12 μmol g^{-1}, whereas clay-sandy soils showed relatively constant values in the study sites. Fig. 9 shows the relationships between different P fractions and other soil variables. Both iron and aluminum oxyhydroxides (Fe-cdb and Al-cdb) are correlated to P-cdb content (Fig. 9). P-cdb was correlated to the Fe-cdb and Al-cdb content of soils with a R^2 of 0.81 and 0.72, respectively. However, soil P-org content showed a different trend: P-org accumulation was strongly correlated to soil C content, with R^2-values above 0.8.

3.5. Hg content variation in soil

Soil Hg content tended to decrease with duration of land-use, especially at the soil surface, eventually stabilizing to reach a rather constant minimum level (Fig. 10). In the first horizon of clay-sandy soils, Hg content went from 70 ppb in forest soils down to around 55 ppb for both crop and fallow after 5 years. At the surface of clayey soils, the 130 ppb median value of Hg in forest sites fell to a threshold value of around 95 ppb for all land-uses; this drop was recorded after the first year of crop. At depth, the drop of Hg through time caused by land-use was less significant. Surface soils lost up to 35% of the original Hg content while deeper soils showed a smaller depletion, up to 10%. In absolute terms, the overall loss for clayey soils was more considerable since the initial value was larger: an approximate average value of 35 ppb of Hg was lost from the top layers of clayey soils, while approximately 15 ppb of Hg was lost from clay-sandy surface soils.

4. Discussion

4.1. Soil chemistry

Chemical variations in soils were observed when comparing farmed land to that of forested sites. Soils in their first crop cycle underwent a Hg depletion similar to that of soils submitted to long-term land-use, especially in the case of clayey soils (Fig. 10). This means that Hg depletion occurs rapidly after deforestation and that simply burning the forest triggers Hg depletion (also see Farella et al., 2006). Hg content does not seem to fall beneath a given threshold indicating that Hg loss attains a limit at a particular soil depth. Other studies in the Amazon region also proved that deforestation causes soil Hg depletion. Roulet et al. (1998) showed that Hg leaching process affects primarily surface horizon. Almeida et al. (2005) observed that 80 cm soil profiles under pasture and silviculture have lower Hg content than soils in forests. Lacerda et al. (2004) measured lower Hg concentrations in surface soils (until 10 cm) under pasture compared to soils in forests. Fostier et al. (2000) clearly demonstrated that deforestation contributes to a three-fold increase in Hg content of a stream output compared to a natural area. Thus, each hectare that undergoes slash-and-burn represents yet another source of Hg to aquatic ecosystems. The rapid Hg loss after deforestation observed in this study constitutes a strong incentive to limit further deforestation.

In an analogous fashion, NH_4 and NO_3 content also diminish right after deforestation and, again, depletion is greater in clayey soils (Figs. 5 and 6). While NO_3 depletion is probably driven by lixiviation, the NH_4 decrease could be related to the competition caused by lasting cations at the surface, as is the case for Hg. Soil N dynamics in the Amazonian region is an important issue since it is a limiting nutrient (Tiessen et al., 1994b). Even without soil perturbation, Amazonian soils suffer from low N retention: NO_3 is a very mobile nutrient subject to leaching while NH_4 is prone to competition with other cations. N is rendered even more mobile after fires and farming because of several processes such as the reduction of OM inputs due to the absence of forest litterfall, stimulation of OM mineralization resulting from higher soil temperatures and increased leaching through rainfall (Brown et al., 1994; Roose, 1986). These processes, added to the N uptake by crops and pasture, might contribute to N depletion after deforestation. A literature review by Murty et al. (2002), which gathers results from 61 sites, emphasizes that average N loss with land-use was 15%. However, not all studies showed this N depletion with land-use. For example, in Amazonia which looked at soils similar to those found in our study site, NO_3 and NH_4 content first increased following slash-and-burn then subsequently decreased but not below forest values (Hughes et al., 2002). Other studies in Rôndonia reported an increase in total N in pasture (Moraes et al., 1996) and more specifically with respect to pasture duration (Feigl et al., 1995).

Base cation content also responds very rapidly after deforestation. It has been shown that post-burn ashes contain around half of the Ca and K originally in tropical forest biomass (Giardina et al., 2000). Base cation enrichment of soils upon forest burning has been widely documented (Juo and Manu, 1996; Sanchez et al., 1983; McGrath et al., 2001). Such enrichment in base cations was indeed observed in the soils of our study which had been cropped only 1 year as well as in soils that had been submitted to pasture for more than a decade. This fertilizing effect is important for agricultural purposes given that K, Ca and Mg are often considered limiting nutrients or at least scarce in Amazonian soils (Jordan, 1984; Cochrane and Sanchez, 1982; Cuevas and Medina, 1988; Sollins, 1998). However, this base cation enrichment is only temporary as illustrated by the Ca content which tended to diminish when fallow time exceeded 15 years, probably due to cation immobilization in the fallow biomass. Depletion of Mg and K also occurred in the years following deforestation, but only in clayey soils. The N limitation in clay-sandy soils may lead to a smaller fallow biomass and therefore to a lower uptake of base cations by successional vegetation. A 20 year chronosequence study in soils under pasture in Rôndonia also showed a cation increase followed by a gradual decline, this trend is greater with Ca than with K and Mg (Moraes et al., 1996). Farming practices executed over a longer time period would probably contribute to stronger base cation depletion (Juo and Manu, 1996; Cochrane and Sanchez, 1982; Fölster, 1986). Decline of nutrients with land-use is known to depend on many factors including lack of vegetation cover, numerous clearings, frequent cultivation sequences, destruction of the forest root mat and reduction of soil biota (Juo and Manu, 1996).

Likewise, a portion of the P contained in the aboveground biomass is deposited on the soil surface after forest burning. The fertilization effect of the ash contributes to the enhancement of P levels in soils. The quantity of P returned to soils through ash has been reported to be comparable to that of base cations, with around half of the P from the biomass reaching the soil surface (Giardina et al., 2000). While the P-org pool is enriched upon deforestation, this is not the case with the P-cdb content. We do not observe any clear trend in the P-cdb fraction, but the effect of long-term fallows and pastures on soil P accumulation reflects the tendency to an increase of the P-org pool. It is noteworthy that the P-org in our study strictly refers to a recalcitrant P form extracted with HCl after combustion, while the P-cdb form of our study is somewhat similar to the Po fraction reported in various studies (Neufeldt et al., 2000; Garcia-Montiel et al., 2000; Linquist et al., 1997; Iyamuremye et al., 1996a,b; Maroko et al., 1999; Ball-Coelho et al., 1993). The correlations shown in Fig. 9 suggest that OM cycling is primarily responsible for regulating P-org inputs once land has been cleared. The clay, Fe and Al-oxides and organic complexes content of oxisols and ultisols promote fixation and immobilization of P (Rao et al., 1999; Ayodele and Agboola, 1981). From our results, it seems that deforestation and land-use are not affecting the P linked to Fe and Al oxy-hydroxides, while that P-org is affected by the cycling of burnt biomass.

There are a few noticeable differences between the soil responses of crops, pastures and fallow. A period longer than 3 years spent in crop contributes to the maximum soil depletion in Hg, NH_4 and C, as well as to lower the initial base cation enrichment. This tendency for nutrient loss through time of cultivation has also been reported by others (Hughes et al., 2002; Fölster, 1986; Sanchez et al., 1983). Moreover, Tiessen et al. (1994a) emphasize that Amazonian soils can support cultivation for only 3 years, because of a naturally low nutrient content, interruption of forest litter cycling and degradation of the existing pool of OM. Pastures may be sustained longer on Amazonian soils than crops because of a lower soil nutrient depletion and higher OM soil content (Murty et al., 2002; Muller et al., 2004; McGrath et al., 2001). In our study though, a period longer than 10 years spent in pasture caused an important depletion of NO_3 and K content. Serrão and Toledo (1990) stated that complete soil coverage with pasture can be much more efficient in reducing soil erosion and maintaining the physical and chemical properties of soils than frequent cropping, but that non-managed pastures might present a high degree of degradation beyond 7 years. The pastures in our study area were generally poorly managed, thus making them more prone to soil degradation. Fallows greater than 15 years tend to help soils recover forest level nutrient content (Figs. 2 and 3). The tendency of fallows to help replenish N content through atmospheric fixation and recycling from sub-soils has been demonstrated elsewhere (Maroko et al., 1998; Schroth et al., 2000). The recovering capacity of fallows depends on many factors such as length of fallow, species diversity and inherent soil fertility (Juo and Manu, 1996).

Soil responses are influenced by the initial soil properties related to texture. Absolute values of Hg depletion are two times greater for clayey soils. In addition to the higher natural Hg content of clayey soils, the greater depletion might also be a direct consequence of greater base cation enrichment (Farella et al., 2006). Indeed, the clay content of soils favours cations retention (Sposito, 1989), and deforested clayey soils retain base cations from the burnt aboveground biomass more easily. In contrast, clay-sandy soils retain the new inputs of base cations less efficiently, leading to less Hg leaching. The maximum loss of Hg for clay-sandy soils was recorded in soils that underwent 3 or 4 years of cropping whereas this loss was more rapid for clayey soils (Fig. 10). The build-up of the P-org pool also responds differently in clayey and clay-sandy soils, with the latter showing a greater increase (Figs. 8 and 9). Forests that grow on clay-sandy soils often develop a denser root mat as well as a deeper root system than soils with higher clay content. The slow degradation of this belowground biomass possibly contributes to enhance the P-org pool in clay-sandy soils. Similarly, gradual degradation of OM from unburned slashed biomass was reported as a source of slow release of P in soils (Garcia-Montiel et al., 2000). However, even with these new soil P sources emanating from slash-and-burn practices, the absolute content of P-org for clayey soils still remains higher than for clay-sandy soils, as was the case for base cations.

4.2. Recommendations for better family farming

Two main incentives drive the call for a more sustainable agriculture in the Amazon region: (1) reduction of soil nutrient depletion in order to allow for long-term land-use and lower deforestation rate; (2) reduction of Hg contamination of aquatic ecosystems and subsequent harm to populations dependant on aquatic resources.

4.2.1. Prioritizing cultivation on clayey soils

Cultivation of clay-sandy soils does not appear to be sustainable, due to their inferior fertility and a more dramatic nutrient loss upon deforestation than clayey soils, especially for available N. Any further N loss would be critical given the existing NO_3 and NH_4 limitations. Pasture management that would favour N fixation (Rao et al., 1999) or at least that would not cause any N depletion (Muller et al., 2004; McGrath et al., 2001; Neill et al., 1995) would therefore be more acceptable than nutrient-demanding crops. The lack of any positive impact of pastures on N content in our data set is probably a consequence of poor management. Considering base cation soil content, again, farming practices appear to be less sustainable on clay-sandy soils according to the fertility index proposed by Cochrane and Sanchez (1982). Both Mg and K contents are often under the limit suggested for infertile soils for clay-sandy soils submitted to land-use. Therefore, new deforestation for farming purposes should be restricted to clayey soils, which can support longer and more complex cultivation sequences, helping to reduce the deforestation rate. Prioritizing cultivation on clayey soils would probably be acceptable from the farmers' perspective, since 70% of them prefer planting on clayey soils (Farella, 2005). Favouring clayey soils would also reduce soil erosion from slopes since they are frequently found on plateaus (Roulet et al., 1998). However, clayey soils undergo greater Hg leaching as a result of their high natural Hg and also the added impact of base cation inputs. Some strategies would be necessary to reduce this adverse effect upon cultivation, like the use of trees, whether inter-planted with crops or left as a border around cultivated areas. Moreover, since three quarters of the study population prefers to plant rice in newly deforested areas, this crop could be reduced to favour manioc, beans and corn (*Zea mays* L.), usually planted in burnt fallow (Farella, 2005).

4.2.2. *Favouring long fallow*

Longer fallows should be encouraged because of their numerous beneficial impacts especially as to a marked reduction of soil erosion. However, longer fallow might not be easily integrated into family farming practices. Presently, the most common fallow duration is 3 years and farmers agree that this is a sufficient length to allow for crop production that covers the household needs (Farella, 2005). Given that the positive effects of long fallowing periods are not well understood, environmental education might be useful to promote them. Managed fallows are an alternative proposed by researchers to ensure longer term soil fertility and to optimize soil land-use, contributing to reduce deforestation rates. For example, fallows enhanced with certain trees or legumes have proven to replenish soil N (Maroko et al., 1998) and to enhance subsequent crop production (Szott et al., 1994). More research is needed to identify appropriate fallow management strategies for specific regions. Factors such as species selection, biomass production, nutrient sequestration, N and P availability, weed competition, mycorrhiza infections, etc., need to be worked out. Hedden-Dunkhorst et al. (2003) demonstrate how fallow vegetation acts as a safety net through enhancing products extraction and thus household incomes and through providing environmental services by increasing soil fertility and flora diversity. Hence, these authors laud the fallow ecosystem for the beneficial role it can play in environmental and socio-economic sustainability. Our results show the soil beneficial impacts of fallows, where trees predominate. In that sense, literature relates various spatial and temporal associations of trees and crops to allow for more sustainable agricultural practices (Szott et al., 1991; Dubois et al., 1996; Leakey, 1999; Rao et al., 1998; Browder and Pedlowski, 2000).

4.2.3. *Promoting soil enrichment*

In order to favour long-term cultivation and diminish the need for further deforestation, alternatives based on nutrient soil enrichment should also be envisaged. Inorganic fertilization has been studied widely; however, K leaching and P fixation remain problematic (Sanchez et al., 1983; Schroth et al., 2000; Rao et al., 1999). Moreover, the high cost of inorganic fertilizers prevents them from being used by local populations. Organic fertilization could possibly overcome these problems (Ball-Coelho et al., 1993; Iyamuremye et al., 1996a,b). A research option lies in organic soil enrichment used with success by indigenous population for centuries, which have contributed to the formation of fertile soils called "Terra Preta do Indio" (Glaser et al., 2001). Cues could also be taken from regional farming practices of the Ecuadorian Amazon where the forest biomass is left to decompose after felling (slash-and-rot) (Mainville et al., 2006). This strategy would need to be tested in Central Amazonia where precipitation is more seasonal. A research-intervention project in Eastern Amazonia proposes shredding fallow biomass, then leaving it to decompose on the ground instead of burning it (chop-and-mulch) (Sommer et al., 2004). Nutrients in soils have proven to be greatly enhanced after this treatment and a financial analysis revealed that this process may double farm incomes (Denich et al., 2004).

5. Conclusion

This paper sheds new light on farming practices and how they relate to Hg leaching and nutrient content in soils. Immediate losses of Hg upon deforestation added to the further progressive loss of N and base cations well illustrate that cropping and pasture have negative impacts on soils. Moreover, there is no indication that fruit tree or banana plantations are better choices in regards to Hg and N loss (Farella et al., 2006). The act of deforestation per se has the strongest impact on soils: indeed, no subsequent land-use can counterbalance the initial Hg loss. These results are of paramount importance for the planning of sustainable farming strategies. An integrated approach which aims to optimize soil fertility and consequently reduce the need for further deforestation should be developed through encouraging cultivation on clayey soils, favouring longer fallows and integrating organic fertilization. The next step is more complex and calls for an alternative to slash-and-burn, as this deforestation method is conducive to Hg leaching. Techniques based on leaving the slashed biomass on the ground could be promising, especially if practiced during the rainy season. This would help to reduce the sudden release of Hg and allow for a more gradual transfer of cations from the slashed forest biomass into the soil for cultivation purposes. But the fact remains that there are already large areas of deforested lands for which more sustainable cultivation practices should be considered based on an intensification of agriculture. Hundreds of thousands of families are presently living from subsistence agriculture, this population growing yearly. Any proposed strategy would have to be discussed with households to verify their appropriateness and chances of success. Sustainable land use on family farms of the Brazilian Amazon needs to be addressed in an integrated manner, taking into account both environmental as well as socio-economic aspects.

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