Mercury release from deforested soils triggered by base cation enrichment

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Abstract

The Brazilian Amazon has experienced considerable colonization in the last few decades. Family agriculture based on slash-and-burn enables millions of people to live in that region. However, the poor nutrient content of most Amazonian soils requires cation-rich ashes from the burning of the vegetation biomass for cultivation to be successful, which leads to forest ecosystem degradation, soil erosion and mercury contamination. While recent studies have suggested that mercury present in soils was transferred towards rivers upon deforestation, little is known about the dynamics between agricultural land-use and mercury leaching. In this context, the present study proposes an explanation that illustrates how agricultural land-use triggers mercury loss from soils. This explanation lies in the competition between base cations and mercury in soils which are characterized by a low adsorption capacity. Since these soils are naturally very poor in base cations, the burning of the forest biomass suddenly brings high quantities of base cations to soils, destabilizing the previous equilibrium amongst cations. Base cation enrichment triggers mobility in soil cations, rapidly dislocating mercury atoms. This conclusion comes from principal component analyses illustrating that agricultural land-use was associated with base cation enrichment and mercury depletion. The overall conclusions highlight a pernicious cycle: while soil nutrient enrichment actually occurs through biomass burning, although on a temporary basis, there is a loss in Hg content, which is leached to rivers, entering the aquatic chain, and posing a potential health threat to local populations. Data presented here reflects three decades of deforestation activities, but little is known about the long-term impact of such a disequilibrium. These findings may have repercussions on our understanding of the complex dynamics of deforestation and agriculture worldwide.

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1. Introduction

In many tropical regions of the world, forests have nearly disappeared or are being seriously endangered. In the Brazilian Amazon, the deforestation rate is fast; around 25,000 km² are being burned annually (23,266 km² for the year 2001–2002, INPE, 2001).
Even though indigenous people have been inhabiting the Amazon for millennia, recent colonization of this relatively low population density region is putting new stresses on the environment. New settlers come to this region to practice subsistence agriculture. By doing so, each family burns on average approximately 1.3 hectares of forest and 2.3 hectares of fallow per year (Farella, 2005). Immigration is severely modifying the landscape in a region that was composed principally of virgin forests 20 years ago. Nowadays, in our study site, 50% of the average 70 hectare familial land is covered with deforested land (Farella, 2005).

Burning the forest is the first step of any agricultural practice in the Amazonian region. Because old tropical soils contain very low levels of available nutrients (Sombroek, 1984), biomass burning is a popular practice for soil enrichment, as most cations of the local ecosystem are found in the vegetation biomass (Fölster, 1986). However, this enrichment is only temporary, as these soils show a poor capacity to retain cations (Spósito, 1989; Jordan, 1984a). After this initial drastic gain, base cations tend to decrease with harvest, rain, erosion and further soil utilization (Farella et al., in press). In fact, numerous studies have demonstrated that the rapid rise of base cations provoked by deforestation is only temporary (Cochrane and Sánchez, 1982; Juo and Manu, 1996). More recently, the loss of Hg from Amazonian soils was also related to deforestation (Roulet et al., 1998; Farella et al., 2001). According to Roulet et al. (1998), Hg adsorbed on fine particles is leached after soil has been submitted to deforestation. Moreover, substantial Hg content increase in sediments appears synchronous with drastic changes in terrestrial inputs of organic matter associated with deforestation (Farella et al., 2001). This Hg leaching from soils is extremely harmful, since it affects human populations after it enters the aquatic food chain. Indeed, in the study region, mercury contamination through fish consumption was associated with declines in coordination, manual dexterity and certain visual functions at levels well below the accepted threshold of 50 μg/g (Lebel et al., 1998).

Traditional disciplinary approaches have led agronomists to study the fate of nutrients in soils and geochemists to study the fate of Hg in soils and in sediments. However, the relationship between these elements has so far never been analyzed. On one hand, it is known that soils gain nutrients after biomass burning, that those nutrients are partly absorbed by cultivation and, ultimately, leached with time. On the other hand, it is suspected that deforestation provokes Hg leaching from soils, consequently contaminating the entire aquatic ecosystem. The aim of the study presented here is to expose the relationships between these two important soil changes. Linking the Hg cycle to the nutrient cycle is of great importance for understanding deforestation and agricultural impacts. In a broader perspective, this study gives some insights for more sustainable family agriculture in the Amazon.

2. Methods

2.1. Research area

The present study is part of a broader research program conducted in a remote region of the Brazilian Amazon, along the Tapajós River. The sampling area was chosen based on collective research needs. The study region is located near the village of Brasília Legal on the banks of the Tapajós River, an important affluent of the Amazon River. Sampling was conducted on family agricultural lands situated within a few kilometers. All of the sampled sites were located on the banks of three lakes belonging to the floodplain of the Tapajós River: Lago Pereira, Lago Cupu and Lago Bom Intento. When questioned, people mentioned living in that area from less than 1 year to up to 37 years (Farella, 2005). The principal land-use in this region is the cultivation of temporary crops (manioc, rice, bananas), interrupted with fallow, and generally ending with pasture. Apart from these cultivation sequences, small areas are dedicated to fruit tree plantations, a marginal land-use. Forest still covers approximately 55% of the family land studied, but each year, a larger percentage is lost to newly cultivated plots (Farella, 2005).

2.2. Sampling and analyses

Soil sampling was conducted with the collaboration of farmers. Sampling was pursued only on sites where farmers 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 farmers, 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. A total of twenty-five family farms were sampled, representing one hundred different sites. At each site, three different cores were sampled with a percussion sampler at approximately 10 m distance from each other. The five first centimeters under the litter was considered as representative of soil surface, while the 20–25 cm horizon and the 50–55 cm horizon were sampled to evaluate pedological dynamics under the soil surface. A forth core was sampled at each site to analyze soil density.
A total of 1200 soil samples were collected, of which 900 were taken back to Canada for physico-chemical analyses.

Various physico-chemical variables were determined. Hg was extracted with HCl and measured by atomic fluorescence (Pichet et al., 1999). Cations (Ca, Mg, K, Al, Fe, Mn) were extracted with BaCl₂ and measured by atomic absorption (Hendershot et al., 1993). Mineral N (NO₃ and NH₄) was extracted with KCl 2M (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, Al and Mn were extracted using the citrate–dithionate–bicarbonate (cdb) buffer method (Lucotte and D’Anglejan, 1985), and analyzed by atomic absorption. The different phosphorus forms (apatite, organic and cdb) were isolated following a sequential extraction and measured by colorimetry (auto-analyzer TRAACS 800) (Lucotte and D’Anglejan, 1985). The pH (H₂O) was determined using a glass electrode in a 1:2 soil:water solution. Density was the only measure done directly in the field, where soil samples of known volume were dried in an oven at 60 °C for 24 h, and then weighed. Granulometric fractions were weighed after humid fractionation: fine particles represent the fraction inferior to 63 μm in size, medium particles represent the fraction comprised between 63 and 210 μm, and large particles are the ones measuring between 210 μm and 2 mm.

Since sampled soils showed a wide variety of color 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 color characterization based on the Munsell chart was made for each dry soil sample. Colors showed a wide gradient of tones from grayish yellow to brownish red. This significant heterogeneity of soil colors prevented grouping, thus, a second method, based on fine particles (FP) content, defined as inferior to 63 μm in size, was chosen to distinguish soil categories. 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 the more yellowish soils, possibly related to the group of ultisols. The soil group characterized by more than 65% FP included mainly reddish and red yellowish soils, possibly related to oxisols. In the rest of the present article, we will use the terminology clay-sandy soils (<65% FP) and clayey soils (≥65% FP) to label these two soil groups.

Descriptive statistics were conducted on the data as inferential statistics were not appropriate to evaluate this type of environmental data. Descriptive statistics are a useful tool to understand the behavior of multiple variables in a unique analysis. Principal component analysis was selected to illustrate the complex relationships between the variables studied. After preliminary analyses and selection of the most accurate data, the 17 most important variables were retained for analysis which was performed using the statistical package SAS. The first and second axes explain altogether approximately 35% of the total variation.

3. Results

3.1. Soil properties of forested and deforested sites according to soil type

There are noticeable differences in soil characteristics after forest cover has been burnt and the land has been used for farming activities. Table 1 reports median values of pedological variables for forested and deforested surface soils for both soil types. This table allows us to evaluate the differences between unperturbed soils and soils which went through deforestation followed by other kinds of land-use. Deforested sites include the following land-uses: pasture, short-cycle crops, fruit tree plantations, banana plantations and fallow vegetation. The history of land-use for each site is quite different, although this diversity is representative of agricultural land-use found in the region. The average time since deforestation is 12.5 years for both soil types on deforested sites. The ratio of “deforested soil/forested soil” (ds/fs) for the selected variables shown in Table 1 (as “change”) gives a good indication of the impacts of farming activities on soil properties. The most stunning differences are found among the cation group. The deforested soils are greatly enriched in the three base cations, Ca, Mg and K, as well as in the trace element Mn, increasing 2- to 9-fold. Cation enrichment is more pronounced in deforested clayey soils than in deforested clay-sandy soils, the effective cation exchange capacity (ECEC) of clayey soils increases twofold. More precisely, the sum of base cations (KCaMg) increases five and a half times on deforested sites for clayey soils, whereas it is four times greater for clay-sandy soils. The rise in base cations has a subsequent effect on pH, which rises from 4.2–3 to 5.2. A second important difference in deforested soils is seen in Hg content of deforested sites, which shows a clear tendency to be depleted in comparison to forested sites. Overall, Hg
depletion after deforestation is more marked in clayey soils, with a 20% drop, compared to a 10% drop in clay-sandy soils. This means that farming on clayey soils implies both a greater enrichment in base cations and a greater loss of Hg. Moreover, it was found that in clayey soils Hg disassociates from large particles to a larger extent than from fine particles, while in clay-sandy soils there is a greater percentage of disassociation from fine particles. Organic matter depletion with deforestation is a third important impact noted in this study. Carbon tends to be depleted in deforested clay-sandy soils, with no marked trend in clayey soils. Ammonium and nitrate levels clearly decrease with farming activities, dropping from 40% to 70%.

3.2. Principal component analysis illustration of base cation against mercury content

Principal component analysis was chosen to verify possible concomitant trends in soils affected by farming practices. Figs. 1–6 present these factorial analyses in both soil types at the surface, 20-cm and 50-cm depths, and feature the relationships between 6 independent variables and 11 dependant variables. The six independent variables represent the historical land-use of each site. The number of forest samples totals 15 in the clayey group and 27 in the clay-sandy group. For deforested site (n = 109 in clayey group and n = 138 in clay-sandy group).
group), time since clearing was found to be up to 37 years and time spent in each category of land-use was determined for each site. Total time dedicated to crop culture (TC) averaged 2.1 years, with a maximum of 7 years. Total time devoted to banana plantation (TB) averaged 0.7 years, with a maximum of 11 years. Total time under pasture (TP) averaged 2.2 years, with a maximum of 13 years. Total time for fruit tree plantation (TFr) reached a maximum of 28 years, although only a few sites actually supported fruit trees. Total time under fallow vegetation (Tfa) had an average duration of 6.2 years, with a maximum of 35 years. For clayey soils, 5 sites were supporting a forest (For), compared to 9 sites for clay-sandy soils. Besides these independent time variables, the principal component analysis featured 11 dependent variables of physico-chemical nature. The set

Fig. 1. Principal component analysis in 50-cm depth of clayey soils. For: forested sites; Tb: time spent in banana plantation; Tc: time spent in crop; Tfa: time spent in fallow; Tfr: time spent in fruit tree plantation; Tp: time spent in pasture; FP: fine particles; Hg-fp: Hg in fine particles; P-cdb: P extracted by citrate–dithionate–bicarbonate.

Fig. 2. Principal component analysis in 50-cm depth of clay-sandy soils. For: forested sites; Tb: time spent in banana plantation; Tc: time spent in crop; Tfa: time spent in fallow; Tfr: time spent in fruit tree plantation; Tp: time spent in pasture; FP: fine particles; Hg-fp: Hg in fine particles; P-cdb: P extracted by citrate–dithionate–bicarbonate.

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Fig. 4. Principal component analysis in 50-cm depth of clay-sandy soils. For: forested sites; Tb: time spent in banana plantation; Tc: time spent in crop; Tfa: time spent in fallow; Tfr: time spent in fruit tree plantation; Tp: time spent in pasture; FP: fine particles; Hg-fp: Hg in fine particles; P-cdb: P extracted by citrate–dithionate–bicarbonate.
of variables illustrated in the factorial analysis was chosen from the 29 variables presented in Table 1. Many variables were put aside to avoid featuring obvious associations that would systematically mask other, unknown relationships. For example, pH, Fe, Al and Mn would constantly draw an opposition against the base cations. Since this relationship is well known and abundantly documented, these variables were dropped. Other variables were left aside because of their strong dependency on soil heterogeneity, and also because they did not seem to be affected by deforestation according to data shown in Table 1. For example, Fe-cdb, Al-cdb, Mn-cdb, Papa and Porg were dropped because of their weak response to agricultural practices (Farella et al., in press). Finally, after preliminary statistical analysis, some variables – like density and humidity – were dropped because of their weak interaction with the others. Once the discrimination of variables was achieved, the 11 most pertinent variables were incorporated in the principal component analysis.

The most important observation seen in Figs. 1–6 is the strong opposition between Hg and base cations. This trend is most clearly seen in soils found at depth under the surface. Fig. 1 illustrates the principal component analysis for 50-cm depth of clayey soils while Fig. 2 shows the same analysis for clay-sandy soils. In both figures, the three base cations are at one end of the first factor, while Hg and Hg-fp are at the other end. These figures show that the principal variation in soils triggered by farming practices consists of enrichment in base cations and a drop in Hg, both changes appearing together. In both figures, the forest variable is not greatly influenced by this trend, but tends to appear related to the Hg variable. Fallow time also shows a similar trend to that of forest, and is even more related to the Hg variable on clay-sandy soils. The only farming use which is also related to the Hg variable is the crop cultivation, which is the only land-use not supporting a closed vegetal cover, often leaving the soil mineral horizons exposed. On the contrary, the three other soil land-uses, which are normally associated with a plant cover, show a tendency to be more related to base cations. Banana plantation is related to base cations on clayey soils but does not seem to have a significant impact on clayey soils. The contrary is true for pastures, which are related to base cations on clayey soils, but not on clay-sandy soils. Plantation of fruit trees is only found on clayey soils and is also related to base cations. All trends described in the 50-cm depth are also observed in the 20-cm depth of both soil types (Figs. 3 and 4): forest, fallow and crops vary with the Hg variable, while banana, pasture and fruit trees do so with base cations. Tendencies observed at the 20-cm depth are even more marked than at the 50-cm depth therefore reinforcing these trends.

For surface soils, the opposition between Hg and base cations is also observed but it takes place as the second most important variation, as indicated by the fact that it runs along the direction of the second factor (Figs. 5 and 6). For clayey soils, the three base cations are the main variables situated at one end of the second axis, whereas
only two base cations (K and Mg) are clearly situated at one end of the second axis for clay-sandy soils. For both soil types, Hg is at the opposite side of base cations on the second axis. As is the case for horizons below the surface, forest soils appear correlated with the Hg variable, showing that a larger amount of mercury is found in undisturbed soils. The time variables characterizing the various farm land-uses are also related to base cations and Hg opposition, and to a relationship illustrated on the first axis as well, as will be discussed below. Considering the opposition between Hg and base cations, we observe that all farm land-uses are closely related to base cations whereas forests and time spent in fallow are related to Hg, this latter land-use on clayey soils only. This tendency of time variables being closely correlated to base cations for the various farm land-uses is similar to what was observed in depth. Moreover, it is clear that the opposition between forest and farm land-use is parallel to the opposition between base cations and Hg. Following this trend, we observe that both forms of available mineral nitrogen, \( \text{NO}_3 \) and \( \text{NH}_4 \), are correlated to Hg. Moreover, for clay-sandy soils, the opposition between farm land-use and Hg-pf is even stronger than it is with Hg, suggesting that the loss of Hg is principally related to Hg associated with the fine particle fraction. In general, all farming activities tended to show a loss of Hg, \( \text{NO}_3 \) and \( \text{NH}_4 \), and enrichment of base cations in surface soils, these relationships appearing associated with the second axis.

4. Discussion

4.1. Soil disequilibrium through new cation input

The eminent findings of our research are the enrichment in cations and the concomitant loss of Hg following agricultural activities. Although these impacts can be deduced from the comparison of forested and non-forested sites in Table 1, the principal component analyses shown in Figs. 1–6 illustrate that these two processes happen together and are influenced by type of land-use. Indeed, while these two processes were already reported in previous studies, their concomitance was never assessed. The clear opposition between Hg and base cations in the principal component analyses leads us to propose an insightful hypothesis, which significantly deepens our understanding of farm land-use on tropical soils. Our hypothesis is that beyond the concomitance of these two processes, the Hg loss is largely triggered by cation enrichment. The input of base cations resulting from the burning of forests is tremendous, as the above-ground vegetation biomass is the main reservoir of cations in highly weathered tropical environments (Fölster, 1986). Given that Amazonian soils are very poor in base cations, the overall content of base cations increases more than fourfold. The principal impact of slash-and-burn agriculture on soils is an improvement of soil chemical properties, especially through a fertility enhancement, which is well known and allows farmers to produce crops on the weathered soils of the humid tropics. While the effect of fertilization in Amazonian soils through slash-and-burn has been well-documented (Juo and Manu, 1996; Cochrane and Sánchez, 1982; Brinkmann and Nascimento, 1973), the present study exposes an adverse effect of this fertilization. The input of base cations is very sudden and sets in motion a previously unknown dynamic in soils which have been submitted to slash-and-burn. Even though some of these base cations are washed away, a significant portion is being retained in soils years after burning (Farella et al., in press). Considering this, we can conjecture that some of these atoms are competing with others already present for soil specific sites. In so doing, other cations are dislocated and may be leached out of the system.

The mineral composition of soils is very important for cation dynamics. Kaolinite represents the most advanced stage of soil weathering and is characterized by the removal of the base cations Na, Ca, Mg and K (Sposito, 1989), and a very low capacity to retain cations (Jordan, 1984a,b). In the clayey soils studied here, the kaolinite’s average content in the surface soil accounted for up to 80% of the fine soil fraction (Poirier, 2003). Moreover, the abundant aluminum and hydrogen in these tropical soils occupy the majority of cationic sites, leaving few sites for base cations (Vitousek and Sanford, 1986). Farming practices modulate the equilibrium that was attained by centuries of forest cover. Our findings suggest that deforestation represents a key step in changing the dynamics of base cations and Hg. For all farm land-uses, the very first impact on soil consists of burning the forest biomass, releasing high level of cations stored in the vegetation (Mackensen et al., 2000; Giardina et al., 2000). Upon their liberation, thousands of these new base cation atoms compete with Hg atoms for specific sites in soils. Based on median values of base cations in forested soils (Table 1), there is a ratio of 30,000 atoms of K, Ca and Mg for one Hg atom in undisturbed soils. This imbalance rises to 215,000 atoms for deforested soils. This input creates a large unbalance for soils, probably leading to a strong competition with Hg.

4.2. Competition between base cations and Hg after deforestation

Very few studies explore the possible competition between base cations and Hg in soils. To our knowledge,
the study that presents the most similarities with our proposed hypothesis was based on a controlled experiment on sandy soils in Finland. The objective being to assess the impacts of increased fertilization on Hg mobility (see Matilainen et al., 2001), this study suggested that soil fertilization led to an increase of Hg mobility, which was related to an increase in loosely bound Hg, ion-exchangeable Hg and reducible Hg, which may be present to the detriment of more stable Hg bonds (Matilainen et al., 2001). In the Matilainen experiment, fertilization addition was approximately 14 g/m² K, 16 g/m² Mg and 26 g/m² Ca. In order to see if the “fertilization effect” of deforestation was comparable to the Finland controlled experiment, we calculated the total weight of base cations added to soils on our sites, which amounted to 3 g/m² K, 5 g/m² Mg and 88 g/m² Ca (see calculus1). These figures, which represent the fertilization effect from biomass burning, are still present in spite of the first year of crop cultivation on clay-sandy soils and are important enough to recreate the conditions of high fertilization reported in the Finland study.

Two other studies added to our understanding of the competition between Hg and other soil components for adsorption sites: 1) Khan et al. (1991) showed that organic pollutants occupy adsorption sites in soil, enhancing Hg mobility and; 2) Mohammad and Jabeen (2003) have demonstrated that in addition to base cations, salt solutions (K and Ca) also enhanced Hg mobility to a greater extent than other metal cations. Finally, a fourth study (Sanchez-Camazano and Sanchez-Martin, 1993) demonstrated that cation enrichment triggered metal mobility in soils and that cadmium mobility was more important in soils with higher base cations content (Ca and Mg).

This competition between base cations and Hg probably occurs on specific sites in soils. In general, cationic elements tend to adhere to clay surfaces and are found on three specific sites (see Sposito, 1989): 1) the most stable sites for cations are in inner-sphere complexes, where cations are trapped inside the clay structure; 2) less stable sites are found in outer-sphere complexes within molecules bound at the surface of clay and; 3) the least stable position is as diffuse ions, a situation in which cations reside in the environs of electronic charges of the clay layers. In light of these three types of bindings, it is more probable that the exchanges among and between base cations and Hg probably occur in diffuse ion sites and, to a lesser extent, in outer-sphere sites. As adsorption sites for cations are also found in humified organic matter for clayey soils (Davies, 1997), some cationic exchanges may then occur within organic matter complexes. However, even if Hg bindings tend to occur preferably on organic substances rather than on mineral surfaces, mineral matter will direct Hg links when organic matter content is low (Schuster, 1991). Indeed, there is a very low content of organic matter in horizons below the soil surface in the region studied (average C at 50 cm is 0.7%; Farella et al., in press), consequently limiting adsorption sites for cations on humified organic matter. Similarly, a study in the same Amazonian region illustrated that C content did not influence Hg behavior in soil, soil Hg accumulation being regulated by iron oxy-hydroxides components (Roulet et al., 1998). In light of these reported facts, it can be put forward that the overall competition between base cations and Hg may first occur around clay structures, and to a more limited extent within humified organic matter.

After deforestation and as a consequence of input of base cations, soil pH raises drastically. Indeed, the pH of forested soils actually went from 4.2 and 4.3 to 5.2 upon deforestation in this study (Table 1). These soils should normally show a greater capacity to retain Hg, as mineral matter presents stronger affinities for Hg when soil pH is above 5 (Biester et al., 2002). However, as explained earlier, the kaolinite capacity for cation retention is low, added to the fact that there is great competition amongst other base cations for these sites. The pH rise may then only weakly contribute to Hg retention. On the other hand, the formation of soluble organic complexes is optimized at a pH above 5, reducing Hg sorption linked to the OM, which then becomes more mobile (Stein et al., 1996). Hg linked to organic matter would then be released with a pH rise (Biester et al., 2002). The situation is reversed for acid, undisturbed, forested soils because OM content controls Hg mobility at pH inferior to 4.5–5 (Schuster, 1991), and Hg reaches its maximal absorption on organic complexes at pH below 5 (Stein et al., 1996).

4.3. Base cations and Hg dynamics in the light of farm uses

The opposition between soil base cations and Hg is the most important impact related to the varied farm
land-uses. In the two horizons below the soil surface, time spent in fallow tends to bring the land back to a situation which is similar to the undisturbed forest, with a low content of K, Ca and Mg. Fallow are young secondary forests, immobilizing nutrients previously released by former land-use and recycling the natural input of cations in an efficient fashion similar to natural forests. Therefore, this land-use tends to show depletion of base cations and maintenance of Hg content in soils.

Time spent in banana plantations, pastures and fruit tree plantations tends to be associated with a higher content of cation and a lower level of Hg in subsoils. These three land-uses all have in common the presence of a vegetation cover as opposed to the exposure of soils to the elements associated with the cultivation of other crops. These systems, as compared to fallows and forests are characterized by a reduced number of species and a simplified structure. This simplicity probably plays a role in the less-efficient nutrient cycling that has been observed. In addition, the presence of an abundant litter on the ground in banana plantations limits cation leaching. This is also the case in some of the fruit tree plantations which feature a bounty of fruit residues in soils (Farella et al., in press). Forage grass might play a similar role for pasture land-use through its dense ground covering. Moreover, frequent fires in pastures could also contribute to the addition of a regular cation input through grass biomass burning, therefore favoring subsequent exchanges between base cations and Hg. Thus, the general dynamics involved for these three land-uses could be summarized as a better retention and a lower intake of base cations, which could have an impact on the Hg levels, through occupying specific soil sites and thus contributing to Hg liberation. Seen from a larger perspective, this process amplifies the initial loss of Hg caused by slash-and-burn.

Time spent in crop cultivation displays a different dynamic. For surface soils, this land-use shows a similar pattern to the other land-uses in that it is associated with enrichment in base cations and Hg loss. However, this dynamic is not reflected in soils under the surface. Crop cultivation is characterized by the maintenance of bare soils for long periods of time, thereby subjecting the soil to leaching from rainfall. In the case of the cultivation of crops which leave soils bare, it seems that although the liberation of cations preceding crop cultivation, whether it be from the burning of a forest or fallow, is observed and important at the surface, contributing to Hg displacement, the lack of soil protection increases the effect of leaching and interferes with base cation retention in soils under the surface. One can assume that Hg in subsoil horizons of crop land-use is not displaced by an excess of cations, but rather by other processes such as lateral erosion and percolation (Lucas et al., 1987; Bravard and Righi, 1989; Roulet et al., 1998).

5. Conclusion

The present study constitutes an important finding needed to enrich our understanding of environmental mercury contamination in Amazonian ecosystems. Previous research has already shown that mercury is leached from terrestrial environments following deforestation and tropical land-use (see Roulet et al., 1998, 1999 for Brazil, Maurice-Bourgoin et al., 2001 for Bolivia and; Mainville et al., 2006). For example, Roulet et al. (1998) estimated that deforestation followed by 6 years of cultivation resulted in a Hg loss of 6 to 13 mg/m². This study allows us to deepen our comprehension of this complex environmental problem by showing that, in addition to erosion processes, natural mercury is being leached from soils as a result of competition from base cations. This new understanding has numerous implications for mercury contamination in the Amazon and worldwide.

Soils of the Amazon region naturally harbour significant loads of Hg even in deep soil horizons (Roulet et al., 1998; De Oliveira et al., 2001). Our results suggest that the constant input of base cations related to the various anthropogenic land-uses in the Amazon may destabilize Hg throughout the soil profile, contaminating rivers and lakes for centuries to come. Cultivation of Amazonian soils may then contribute to a constant leak in this nearly infinite Hg reservoir. Moreover, the aquatic ecosystems of the Amazon are quite efficient at methylating Hg and bioconcentrating it in the food chain. Abundance of macrophytes and high temperatures are among the favorable conditions which enable the transformation of inorganic Hg to its organic form (Guimarães et al., 2000). Furthermore, Hg leaching is particularly harmful for local populations since they rely on fish in their diet (Lebel et al., 1998; Dolbec et al., 2001; Passos et al., 2004; Webb et al., 2004). Therefore, intervention projects should aim at reducing the release of Hg toward aquatic ecosystems through management of farm land-use (Farella et al., in press).

This research sheds new light on the Hg contamination problem in the Amazon and worldwide. In Canada and Mexico, studies have shown that forest fires contribute to Hg contamination of lakes (Garcia and Carignan, 1999, 2000; Caldwell et al., 2000). Studies should be pursued in Northern environments, especially given that natural
boreal forest dynamics are based on fire cycles. More particularly, future research should evaluate if and how this dynamic manifests itself in different soils which may have a stronger cation retention potential. Whilst this paper argues in favor of the urgent need to implement a more sustainable family agriculture in the Amazonian region, it also points to the need for studies on natural and anthropogenic forest perturbations elsewhere.

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