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Early Hg mobility in cultivated tropical soils one year after slash-and-burn of the primary forest, in the Brazilian Amazon

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ABSTRACT

In the Brazilian Amazon, forest conversion to agricultural lands (slash-and-burn cultivation) contributes to soil mercury (Hg) release and to aquatic ecosystem contamination. Recent studies have shown that soil Hg loss occurs rapidly after deforestation, suggesting that Hg mobility could be related to the massive cation input resulting from biomass burning. The objective of this research was to determine the effects of the first year of slash-and-burn agriculture on soil Hg levels at the regional scale of the Tapajós River, in the state of Pará, Brazilian Amazon. A total of 429 soil samples were collected in 26 farms of five riparian communities of the Tapajós basin. In September 2004, soil samples were collected from primary forest sites planned for slash-and-burn cultivation. In August 2005, one year after the initial burning, a second campaign was held and the exact same sites were re-sampled. Our results showed that total Hg levels in soils did not change significantly during the first year following slash-and-burn, suggesting no immediate release of soil Hg at that point in time. However, an early Hg mobility was detected near the surface (0–5 cm), reflected by a significant shift in Hg distribution in soil fractions. Indeed, a transfer of Hg from fine to coarser soil particles was observed, indicating that chemical bonds between Hg and fine particles could have been altered. A correspondence analysis (CA) showed that this process could be linked to a chemical competition caused by cation enrichment. The regional dimension of the study highlighted the prevailing importance of soil types in Hg dynamics, as shown by differentiated soil responses following deforestation according to soil texture. Confirming an early Hg mobility and indicating an eventual Hg release out of the soil, our results reinforce the call for the development of more sustainable agricultural practices in the Amazon.

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1. Introduction

As political and economic factors have led to a massive migration towards the Brazilian Amazon during the last forty years, thousands of families have established in rural communities to practise subsistence activities (Laurance, 2000). The intensification of the occupation of the Amazon – which contains the largest tropical forest in the world (Sioli, 1984) –, has caused a marked acceleration of the deforestation rate (Almeida and Ozorio Campari, 1995; Mahar, 1989). By the year 2004, more than 17% of the Amazon forest had already been cleared (Margulis, 2004).

At local and global scales, deforestation in the Amazon has pronounced environmental, social and economical impacts (Laurance, 2000). It has important effects on climatic and hydrological systems (Cochrane et al., 1999; Laurance, 2000; Nepstad et al., 2000, 2001),

carbon reservoirs (Fearnside, 2003; Laurance, 2000; Soares-Filho et al., 2006), atmospheric emissions of chemical compounds (Fabian et al., 2005), landscape fragmentation (Metzger, 2003), biodiversity (Fearnside, 1999), river sediments (Farella, 1998; Farella et al., 2001) as well as on soil fertility (Béliveau, 2008; Cochrane and Sánchez, 1982; Farella et al., 2007; McGrath et al., 2001; Murty et al., 2002). Furthermore, a relationship between deforestation and mercury (Hg) contamination of aquatic ecosystems has been recently shown (Farella, 2005; Farella et al., 2006; Roulet et al., 1998, 1999, 2000). This has important implications for human health in Amazonian communities (Dolbec et al., 2000; Fillion et al., 2006; Lebel et al., 1998), which are exposed to mercury contamination through their elevated fish consumption (Bastos et al., 2006; Dolbec et al., 2001; Lebel et al., 1997; Passos et al., 2001, 2007; Webb et al., 2004).

While a significant part of the deforestation is attributed to large farms and extensive pastures (Cohenca, 2005; Margulis, 2004), family farming plays an increasingly important role as well (Farella, 2005). Slash-and-burn is the most common deforestation practice in small family farms of the Amazon (Benhin, 2006; Farella, 2005). This method consists of manually cutting a forest plot before burning the residual plant biomass. The nutrient-rich ashes coming from the burnt

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forest are a natural fertilizer for tropical lands (Nye and Greenland, 1964), bringing new nutrient inputs into cation-depleted soils and reducing their acidity (Bêliveau, 2008; Fabian et al., 2005; Farella et al., 2007; Mainville et al., 2006; Nye and Greenland, 1964). However, this fertilization is of short duration (Cochrane and Sánchez, 1982) and after the cation concentration peak usually observed following slash-and-burn, a gradual decrease frequently occurs, often just a few years after the burn (Nye and Greenland, 1964). High precipitation and intense climatic conditions are factors contributing to nutrient leaching and soil erosion (Maurice-Bourgoin et al., 2000; Wick et al., 2005). This short-term fertilization often leads family farmers to cultivate the same burnt land for only one to a few years before leaving it in fallow (Farella, 2005). Facing rapid soil nutrient depletion, they are obliged to continually cut and burn new plots of land, leading to an unsustainable use of their forest capital.

The role of deforestation in soil Hg release is still being debated. Some authors affirm that small-scale mining is the main cause of Hg contamination of aquatic ecosystems (Miller et al., 2003), through the massive use of this metal in gold extraction methods (Veiga and Baker, 2004). However, many researchers found that a release of natural soil Hg occurred following deforestation, contributing to the presence of this metal in the aquatic environment, especially further away from gold-mining areas (Almeida et al., 2005; Bastos et al., 2006; Lacerda et al., 2004; Lechler et al., 2000; Roulet et al., 1999). There is a growing evidence that slash-and-burn could be responsible for the bulk of Hg liberation (Lacerda, 1995). Some studies have concluded that forest and litter combustion (Engle et al., 2006) as well as high temperature in deforested sites (Magarelli and Fostier, 2005) resulted in an important Hg release. Moreover, Farella et al. (2006), who studied the relationship between land use and soil Hg dynamics in the Tapajós region, found a loss of Hg that went up to 35% in soils subjected to multiple cultivation sequences, up to 15 years after deforestation. The Hg loss was mostly observed in surface horizons and in soils with higher clay contents. Farella et al. (2006) suggested that Hg loss following deforestation could be triggered by the massive input of base cations contained in ash coming from burnt vegetation. Indeed, these cations could chemically

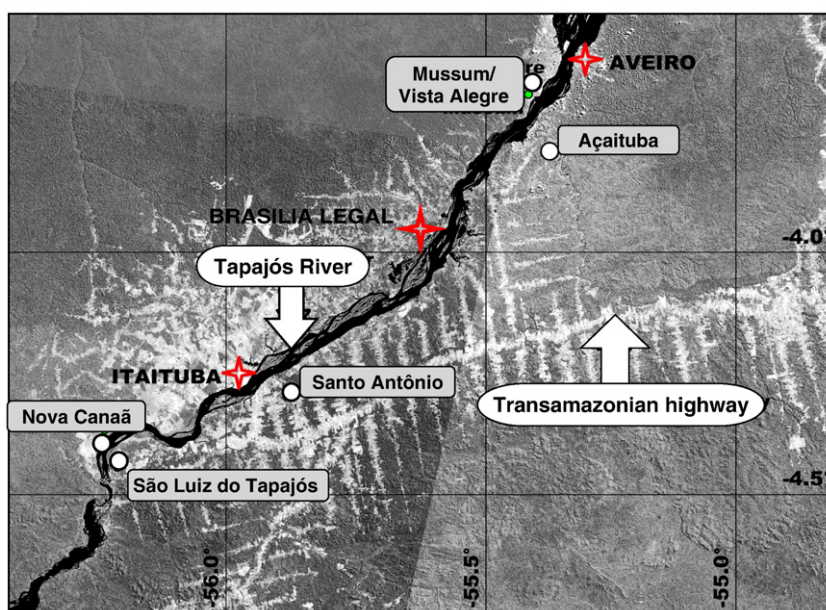
compete with Hg atoms on adsorption sites of clay particles, increasing the mobility of the contaminant (Farella et al., 2006).

Although several authors have worked on soil Hg dynamics following deforestation in the Ecuadorian (Mainville et al., 2006), Bolivian (Maurice-Bourgoin et al., 2000, 2003) and Brazilian (Almeida et al., 2005; Farella, 2005; Farella et al., 2001, 2006; Poirier, 2003; Roulet et al., 1998, 1999, 2000) Amazon, none of them studied the immediate response of soils after having been cleared. Our study was designed to allow a precise analysis of Hg dynamics in recently deforested soils. The sampling design consisted of repeated soil sampling at the exact same sites 1) before primary forest disturbance and 2) one year after the initial burning. Based on recent findings (Farella et al., 2006), we expected that changes in soil properties and in soil Hg levels would occur rapidly following deforestation. The objective of our study was to characterize the effects of the first year of slash-and-burn cultivation on soil Hg dynamics in family farms of the Tapajós region. Moreover, in contrast to Farella et al. (2006) who focused specifically on farms established within a few kilometres around the village of Brasília Legal, our research aimed at analysing soil responses to deforestation at a larger scale, in five communities located on a 150 km north-south gradient along the Tapajós River. We expected that regional patterns related to the varying soil types and textures existing in the region would influence Hg dynamics.

2. Methods

2.1. Study area

This study was part of the Caruso research project conducted by a joint Canadian and Brazilian team working, with an ecosystem and interdisciplinary approach, on the relationships between Hg, human health, the environment and land transformation in the Tapajós region. The study area is located in the State of Pará (Brazilian Amazon) in the Lower Tapajós basin (Fig. 1). The project was carried out in a 150 km segment of the river, between the municipalities of



* Studied communities are identified by the symbol ○ and major communities are identified by the symbol ★

Fig. 1. Location map of the study area.

Aveiro and Itaituba. All studied sites were located between 03°40' to 04°28'S and 56°12' to 55°21'W.

The region, with an annual rainfall varying between 1800 mm and 2200 mm, is characterized by a relatively short dry season (Grupo de Trabalho Interministerial, 2004) and by various types of rain forests and some areas of savannas (Embrapa Amazônia Oriental, 2007a). Natural vegetation in the region has already been widely altered, and secondary forests (*capoeiras*) and pastures are very common (Embrapa Amazônia Oriental, 2007b). Soils, which developed on the Alter-do-Chão geological formation (Roulet et al., 1998), are predominantly classified as Oxisols and Ultisols (USDA system) (Soil Survey Staff, 1999), or Latossolos and Argissolos (Brazilian system) (Embrapa Amazônia Oriental, 2007c). They are naturally rich in Hg, which binds on iron and aluminium oxides-rich clays (Roulet and Lucotte, 1995; Roulet et al., 1998). These soils are relatively acidic and poor in nutrients; for millions of years, they have been highly weathered by intense precipitations and strong climatic variations which caused the depletion of nutrients and minerals (Jordan, 1985). The Tapajós Region is an active front of colonization that has been submitted to important demographic, cultural and environmental transformations related to the intensification of the exploitation of the territory in the last forty years (Farella, 2005). Today, family agriculture is the primary means of subsistence in rural areas and is one of the principal deforestation agents (Farella, 2005). Small farmers, who practice agriculture with rudimentary methods on a few tens of hectares (Grupo de Trabalho Interministerial, 2006), usually cultivate temporary crops after the slash-and-burn of the forest. After a few crops and fallows alternating sequences, lands generally end in pastures (Farella, 2005). In our sampling sites, the main crops were cassava or bitter manioc (*Manihot esculenta* Crantz), rice (*Oryza sativa* L.), beans (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.), and to a lesser extend, banana (*Musa* spp.), cacao (*Theobroma cacao* L.), coffee (*Coffea arabica* L.) and pepper (*Piper nigrum* L.).

2.2. Data collection

This research was based on a participatory approach and data were collected in cooperation with the local population. Farms were selected according to landowner participation and site availability. Sites had to be primary forests plots planned for slash-and-burn before the next rainy season and for subsequent cultivation. Based on these conditions, a total of 429 soil samples were collected in 26 sites located on family farms of the riparian communities of São Luiz do Tapajós, Nova Canaã, Santo Antônio, Açaituba and Mussum/Vista Alegre, in the Tapajós basin (Fig. 1).

In September 2004, soil samples were collected from primary forest sites, carefully discarding areas that had been affected by former anthropogenic activities. In August 2005, a second sampling campaign was held at the same sites, one year after the slash-and-burn of the forest. Samples collected in 2005 (i.e. after deforestation) were taken 30 cm away from the holes dug in 2004 (i.e. before deforestation). Since first sampling points had been tagged and were maintained by participating farmers, it was possible to re-sample the next year at the exact same place. However, for various reasons (selected forests not cleared, sampling sites not clearly identified or landowners not available), only 21 of the 2004 sites were re-sampled in 2005.

In each community, four to seven sites were sampled. For each site, soil was collected at three representative points. After having removed organic litter at soil surface (leaves and branches), one soil sample was taken at three different depths (0–5, 20–25 and 50–55 cm) with a 100 cm³ percussion sampler. The 0–5 cm horizon was considered as representative of soil surface while 20–25 cm and 50–55 cm horizons where sampled in order to analyse subsurface soil dynamics.

This research design allowed us to analyse Hg dynamics during the first year following deforestation, taking into account soil depth and regional variation.

2.3. Laboratory analyses

During the sampling campaigns, samples were air-dried to reduce soil moisture. All samples were taken back to Canada for laboratory analysis. They were oven-dried at less than 40 °C, in order to avoid Hg volatilization, until a stable weight was obtained. Dry weights were recorded and bulk density (dry weight/100 cm³) was calculated. Each sample was then divided in two parts. The first part was kept unsieved for granulometric determination and subsequent analysis of Hg on soil fractions. The second part of the samples, after having been 1) passed through a 2 mm sieve to remove small rocks and roots, 2) reduced to a fine and homogeneous powder with a steel percussion grinder and 3) lyophilised to remove interstitial water, was used for all remaining laboratory analysis.

Available base cations (Ca, Mg, K, Al, Mn and Fe) were extracted with BaCl₂ and measured by atomic absorption (Hendershot et al., 1993), and pH was determined with a glass electrode after a 1:4 dilution in water. Fe and Al oxy-hydroxides (Fe_{cdB} and Al_{cdB}) were extracted with citrate–dithionate–bicarbonate and measured by atomic absorption (Lucotte and d'Anglejan, 1985). Total Hg was extracted with HCl and was then measured by atomic fluorescence (Pichet et al., 1999).

Soil granulometry was determined after humid fractionation of the untreated sub-samples. Using sieves with three different meshes, we obtained three distinct groups of particles: 1) a fine fraction (later on referred to as “fp” in the text), roughly representing classical clay and silt with diameters smaller than 63 µm grouped together, 2) a medium fraction (referred to as “mp” in the text) between 63 and 210 µm, and 3) a coarse fraction (referred to as “cp” in the text) between 210 µm and 2 mm particles (Grandmont, 2001). This classification was used throughout the previous studies of the Caruso project carried out in the Tapajós Region. We chose to maintain this system because many significant relationships have been found between these granulometric fractions and soil physico-chemical variables, including Hg. Dried fractions weights were recorded and soil granulometry was determined. Hg concentration on soil fractions was then analysed with the method mentioned earlier. Soil granulometry and Hg analysis on fractions have been assessed for one sample randomly selected among the three soil replicates of each site and was limited to the two upper soil horizons (0–5 and 20–25 cm). Throughout this paper, Hg associated to soil fractions will be expressed as Hg-fp, Hg-mp and Hg-cp. In order to ensure the validity of the results, replicates and analytical blanks were included in each protocol. Soil pH was measured at the Biodôme de Montréal, while all the other analyses were done in the GEOTOP laboratory, at the Université du Québec à Montréal.

2.4. Statistical analyses

In order to study the combined impact of slash-and-burn and cultivation on soil properties and on Hg dynamics, the 21 sites that were re-sampled after deforestation were used in the statistical analyses.

In order to first evaluate overall soil dynamics, statistical tests that account for all studied properties were preferred. Since most of our variables did not fulfill the requirements for principal component analysis (i.e. multi-normality), correspondence analyses (CAs) were used. Various preliminary analyses led us to select the 18 most pertinent variables. Values for samples collected in undisturbed sites as well as one year after slash-and-burn were plotted together in the model. Taking into account global soil properties, independently of site condition (before or after burn), associated variables are grouped together on the graphs. Variables positioned distantly along the first or second axis are contrastingly in opposition in the studied soils. The CA is not a measure of an impact (or change) as all samples pre and post-fire are included, but it is a good illustration of the overall characteristics of studied samples and of soil variable interrelations. Two CAs were done, the first one including all samples for the surface

Table 1
Soil properties at 0–5 cm.

Soil variables	Clayey sites mean ± SD (n = 39)			Sandy sites mean ± SD (n = 22)		
	Before	After	df/fs	Before	After	df/fs
Granulometry						
Density (g cm ⁻³)	1.15 ± 0.12	1.23 ± 0.12	1.06*	1.31 ± 0.17	1.36 ± 0.18	1.04*
% cp (210 µm–2 mm)	27 ± 12	32 ± 16	1.17*	48 ± 11	50 ± 11	1.04
% mp (63–210 µm)	34 ± 9	38 ± 9	1.13	37 ± 9	39 ± 9	1.06
% fp (<63 µm)	39 ± 16	29 ± 11	0.76*	15 ± 7	11 ± 3	0.74*
Mercury						
Hg (ng g ⁻¹)	121 ± 33	118 ± 32	0.98	61 ± 25	70 ± 30	1.14*
Hg (ng cm ⁻³)	137 ± 35	144 ± 38	1.05*	77 ± 26	92 ± 34	1.18*
Hg-cp (ng g ⁻¹)	53 ± 21	69 ± 35	1.29*	13 ± 5	18 ± 8	1.41*
Hg-mp (ng g ⁻¹)	92 ± 43	105 ± 38	1.14	55 ± 32	63 ± 27	1.15
Hg-fp (ng g ⁻¹)	205 ± 69	191 ± 63	0.93*	221 ± 59	201 ± 54	0.91*
Cations						
CaMgK (cmol kg ⁻¹)	0.83 ± 0.67	1.62 ± 1.57	1.96*	1.12 ± 1.10	1.73 ± 1.78	1.54
Fe _{cdB} (µmol g ⁻¹)	241 ± 111	237 ± 108	0.98	82 ± 57	78 ± 71	0.96
Al _{cdB} (µmol g ⁻¹)	141 ± 53	136 ± 61	0.96	57 ± 26	59 ± 45	1.03

* means that there is a significant variation following deforestation (paired *t*-test, *p* < 0.05).

horizon, and the second one with samples of the 20–25 cm horizon. Depending on the horizon, the CA inertia (i.e. total data variance explained by the model) varied from 14 to 18%. Furthermore, in both CAs, the two first axes explained altogether about 82% of the total variance of the model.

Descriptive statistics were then used to determine the effect of deforestation followed by a 1-year cultivation period on individual soil properties for a given horizon. As we were interested in soil response following disturbance, where values at *t*₂ depend on values at *t*₁, we used statistical tests for paired samples. After having verified the normality of the distribution of the desired variables, we used multivariate analyses of variance (MANOVAs) to compare their mean concentrations measured before slash-and-burn and one year after (using the means of all sites of a given texture). Student-*t* and Wilcoxon tests were used to compare means between soil types at initial state (unpaired samples). Most of the statistical analyses were done with the JMP 5.1 program (SAS Institute, 2003), except the correspondence analyses that were done with the CANOCO 4.54 program (Plant Research International, 2005).

2.5. Soil classification

A discrimination method for soil classification was worked out to help contrasting soil responses following deforestation. First, a method based on soil colors using the Munsell Chart was tested. All our samples were part of the yellow–red Munsell sheets, but since a wide range of subtle nuances were observed, no soil classification based on color pattern could be established. Since fine particles play a key role in numerous geochemical and pedological dynamics (Brady and Weil, 2002), this variable was selected as a basis for soil classification. Several discriminant analyses led us to adopt a 35% fp threshold in order to create two groups of samples that were distinct according to their overall characteristics (Béliveau, 2008). Hence, in this paper, samples containing less than 35% fp will thereafter be referred as “sandy soils”, and those containing more than 35% fp, as “clayey soils”.

3. Results

3.1. Soil characteristics before slash-and-burn

Firstly, initial soil Hg concentrations were compared in order to determine if geographic distribution has an influence on soil Hg levels

in undisturbed forests. Hierarchical analyses indicated that at soil surface, 64% of the total Hg variability occurred between the sites, compared to 26% between the communities and 10% between the replicates. Since no particular pattern related to the regional distribution was observed and since site heterogeneity seemed to prevail on inter-community variation, an approach based on soil texture was adopted. For details about Hg dynamics by community, see Béliveau, 2008.

At the initial state, soil properties and Hg were generally influenced by soil texture. Sites having a finer granulometry were richer in Hg; a significant relationship (*r*² = 0.28, *p* < 0.0005) existed between % fp and total Hg concentrations in undisturbed soils. Clayey sites exhibited a mean Hg concentration of 121 ng/g at soil surface, compared to 61 ng/g for sandy sites. At the soil surface, the difference between the two groups was very highly significant (Wilcoxon test, *p* < 0.0001), but the gap was attenuated at lower depths. For both soil textures, there was a marked Hg enrichment through the soil profile (Hg concentrations reached 155 ng/g for clayey sites and 114 ng/g for sandy sites at the 50–55 cm horizon (Tables 1 and 2; results for 50–55 cm not shown).

Fig. 2 shows that in primary forests, for both 0–5 cm and 20–25 cm horizons, Hg levels in soil fractions (Hg-fp > Hg-mp > Hg-cp) significantly differed (Wilcoxon test followed by each pairs student test, *p* < 0.0001), for clayey soils (represented by different capital letters) as much as for sandy soils (different lower-case letters). Overall, for combined soil types, about 60% of the total Hg at the 0–5 cm horizon was found in the soil fine fraction, whereas at 20–25 cm, 73% was contained in the fine fraction. Fig. 2 also illustrates that the fine fraction of sandy sites had higher Hg levels than that of clayey sites. Indeed, a significant inverse relationship (*r*² = 0.16, *p* < 0.0092) between % fp and Hg-fp concentration existed at initial state, indicating that Hg tended to accumulate more readily on fine particles when they were scarcer.

Total Hg levels at initial state were correlated with Fe_{cdB} (*r*² = 0.22, *p* < 0.0024) and Al_{cdB} (*r*² = 0.38, *p* < 0.0001) levels. At 0–5 cm as well as at 20–25 cm, the mineral levels were approximately two to three times higher in forested clayey soils than in forested sandy soils (241 compared to 81.2 µmol/g of Fe_{cdB}, 141 compared to 57.2 µmol/g of Al_{cdB}). Soil Fe_{cdB} and Al_{cdB} concentrations were correlated with clay content (*p* < 0.0009, *r*² = 0.25 and *p* < 0.0001, *r*² = 0.33 respectively). In contrast, undisturbed sandy soils surprisingly had a higher sum of base cations (CaMgK), which was mostly driven by relatively high

Table 2
Soil properties at 20–25 cm.

Soil variables	Clayey sites mean ± SD (n = 38)			Sandy sites mean ± SD (n = 22)		
	Before	After	df/fs	Before	After	df/fs
Granulometry						
Density (g cm ⁻³)	1.36 ± 0.25	1.36 ± 0.30	1.00	1.46 ± 0.12	1.46 ± 0.11	1.00
% cp (210 µm–2 mm)	18 ± 9	20 ± 11	1.11	37 ± 8	38 ± 7	1.03*
% mp (63–210 µm)	32 ± 13	35 ± 15	1.11	35 ± 10	37 ± 9	1.05
% fp (<63 µm)	50 ± 24	44 ± 41	0.88*	28 ± 4	25 ± 9	0.90
Mercury						
Hg (ng g ⁻¹)	140 ± 0	137 ± 0	0.98	105 ± 32	103 ± 32	0.98
Hg (ng cm ⁻³)	187 ± 44	182 ± 42	0.97	151 ± 40	148 ± 37	0.98
Hg-cp (ng g ⁻¹)	37 ± 24	49 ± 41	1.34*	16 ± 9	11 ± 3	0.68*
Hg-mp (ng g ⁻¹)	104 ± 47	104 ± 58	1.00	62 ± 36	61 ± 25	0.99
Hg-fp (ng g ⁻¹)	227 ± 61	225 ± 62	0.99	252 ± 60	249 ± 57	0.99
Cations						
CaMgK (cmol kg ⁻¹)	0.28 ± 0.25	0.25 ± 0.26	0.91	0.20 ± 0.17	0.25 ± 0.32	1.25
Fe _{cdB} (µmol g ⁻¹)	296 ± 145	279 ± 148	0.94	121 ± 69.9	111 ± 63.8	0.92*
Al _{cdB} (µmol g ⁻¹)	185 ± 75.5	164 ± 90.1	0.89*	96.2 ± 46.4	83.1 ± 23.0	0.86

* means that there is a significant variation following deforestation (paired *t*-test, *p* < 0.05).

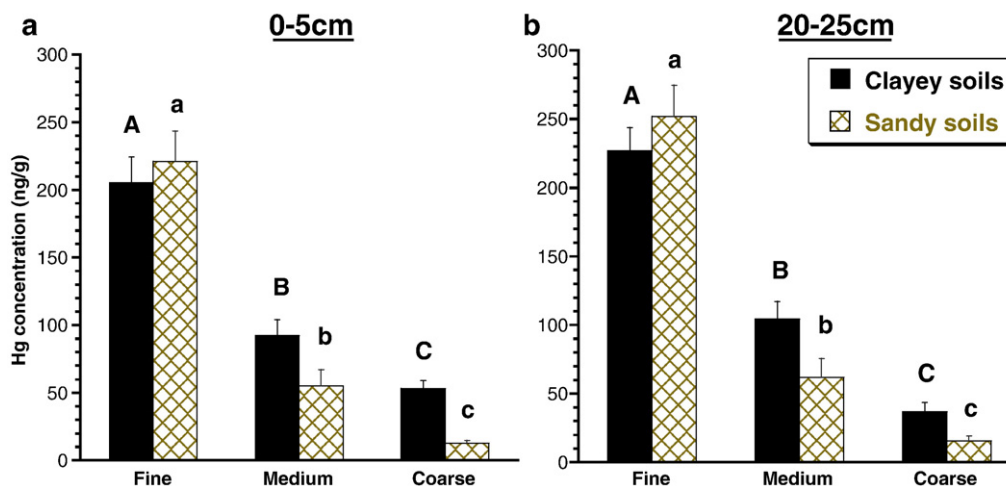


Fig. 2. Hg distribution in relation to soil granulometric fractions and to soil texture at initial state, for the 0–5 and 20–25 cm horizons. Different letters mean significantly different Hg concentrations (mean ± SD) between soil fractions for a given texture (Wilcoxon test followed by each pair student test, $p < 0.0001$). Capital letters represent Hg levels in clayey soils, and lower-case letters in sandy soils.

calcium (Ca) concentrations. Interestingly, inverse relationships between soil total Hg and cations ($r^2 = 0.21$, $p < 0.0001$) as well as between soil Hg-fp and cations ($r^2 = 0.27$, $p < 0.0004$) existed already in undisturbed soils (Fig. 3). This inverse relation between total Hg and cations was significant in both soil textures ($r^2 = 0.31$, $p < 0.0001$ for clayey soils and $r^2 = 0.38$, $p < 0.0001$ for sandy soils). However, the opposition between Hg-fp and cations was significant in clayey sites ($r^2 = 0.34$, $p < 0.0017$), but not in sandy sites ($r^2 = 0.34$, $p < 0.0184$). In forests, for both textures, there was a F_{ecdb} , Al_{cdb} , density, % fp and Hg-fp increase in soil profile. However, cation depletion was generally observed in deep horizons (Tables 1 and 2; results not shown for 50–55 cm).

3.2. Overall soil dynamics and interrelations between physico-chemical characteristics illustrated by correspondence analyses (CAs)

In order to analyze the complex interrelations between the studied variables, taking into account all pertinent physico-chemical soil properties, correspondence analyses (CAs) were done using values for all samples collected before and after slash-and-burn. CAs were produced for 0–5 cm (Fig. 4.a) and 20–25 cm horizons (Fig. 4.b)). In

these models, most of the data variance was explained by the first axis (69.8% for the 0–5 cm and 69.9% for the 20–25 cm horizons) (for more details about CAs eigen values, see Bêliveau, 2008). For the 0–5 cm horizon, since variables such as Al_{cdb} , Fe_{cdb} and most P forms (all related to soil fp) are positioned in proximity to % fp along the first axis (and in clear opposition with % cp), the first axis seems to represent a textural gradient. The high percentage of variance related to the first axis confirms the important effect of soil textural gradient on soil properties.

Between 11 and 13% (for the 0–5 cm and 20–25 cm horizons respectively) of the total data variance was explained by the second axis. Interestingly, at 0–5 cm, total Hg and Hg-cp were positioned in opposition to the sum of base cations (CaMgK) on the second axis (Fig. 4.a)). At 20–25 cm, although not as marked for total Hg, the same opposition between total Hg and Hg-cp to base cations was observed (Fig. 4.b)).

Moreover, we observed that Hg-cp was positioned in proximity to % fp along both axes for the 0–5 cm horizon (Fig. 4.a)), but this association was not observed in soil depth. For the 0–5 cm horizon, the CA showed a clear opposition on both axes between % cp and Hg-cp (Fig. 4.a)). For the 20–25 cm, this opposition also existed on the first axis but it was of a lesser importance on the second axis (Fig. 4.b)).

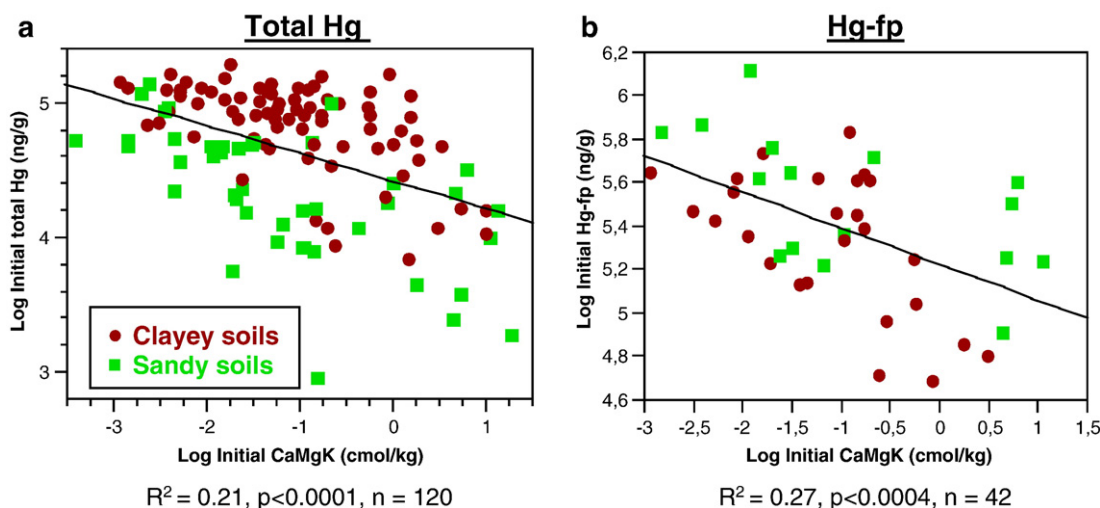


Fig. 3. Relationships between initial cations content and initial total Hg and Hg-fp.

3.3. Hg and soil properties changes following slash-and-burn and a 1-year cultivation period

Tables 1 and 2 provide soil physico-chemical property means for sites sampled before slash-and-burn and one year after the first months of cultivation. These tables show the impacts of land-use on studied variables for the two upper horizons and according to soil texture (13 clayey and 8 sandy sites, each site generally containing three replicates). The “ds/fs” column (ratio of mean values for deforested soils/forest soils) is an indicator of the changes that occurred in soil properties following deforestation.

3.3.1. Soil density and texture

A clear increase in density occurred in both soil textures at soil surface, but no significant variation was observed for deeper horizons (Fig. 5). Sandy sites, which were denser at initial state, had a less marked – but still significant (ds/fs = 1.04, $p < 0.0445$) – surface density increase than clayey sites (ds/fs = 1.06, $p < 0.0002$). Moreover, both textures underwent a loss of fp following deforestation at 0–5 cm as at 20–25 cm (Tables 1 and 2). The loss was more marked at soil surface, where a fp loss of about 25% occurred. Moreover, fp loss (12% of initial fp content) was still significant at the 20–25 cm horizon of clayey soils. The fp loss was also more pronounced in clayey sites; a significant inverse relationship ($r^2 = 0.24$, $p < 0.0002$) was found between fp content of undisturbed sites and their fine particles loss following slash-and-burn cultivation. This inverse relationship was

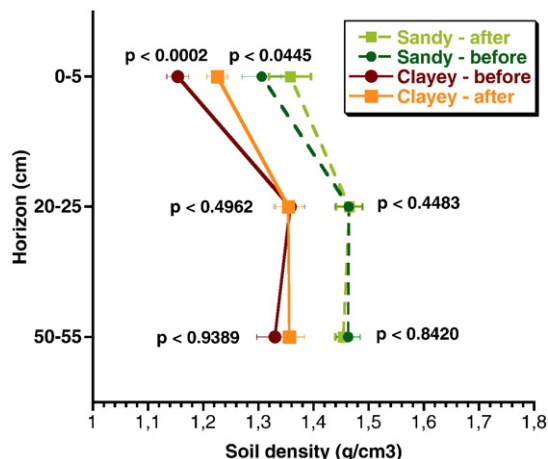


Fig. 5. Changes in soil density in relation to depth upon deforestation and a 1-year cultivation period for two soil textures. * $p < 0.05$ values (paired t -test results) indicate that there is a significant density change for a given horizon and a given soil type. * Error bars represent the standard deviation (SD).

even more accentuated when looking at fp dynamics at the soil surface horizon only ($r^2 = 0.53$, $p < 0.0002$).

3.3.2. Soil total Hg

Overall, there was no marked variation in total Hg after the first year of slash-and-burn cultivation. However, Hg concentrations (ng/g) seemed to be affected differently according to soil texture, especially at soil surface (ds/fs ratios of 0.98 for clayey sites and of 1.14 for sandy sites). Hg concentrations in clayey soils did not change significantly at 0–5 cm (paired t -test¹, $p < 0.1092$), 20–25 cm ($p < 0.0653$) and at 50–55 cm ($p < 0.2253$), whereas we observed a slight but significant Hg increase at surface horizons of sandy soils ($p < 0.0030$), with Hg concentrations going from 61 to 70 ng/g (Table 1). However, there were no marked Hg changes at 20–25 cm ($p < 0.2387$) and at 50–55 cm ($p < 0.2891$) in sandy sites (Table 2; results not shown for 50–55 cm).

Considering total soil Hg burdens (ng/cm³), which takes into account eventual soil density changes, we found a significant Hg burden increase at 0–5 cm in clayey ($p < 0.0043$) as in sandy ($p < 0.0014$) soils. Total Hg burden at soil surface went from 137 to 144 ng/cm³ in clayey sites (ds/fs = 1.05), and from 77 to 92 ng/cm³ in sandy sites (ds/fs = 1.18) (Table 1), but Hg burdens of both soil textures did not change significantly in subsurface horizons (Table 2).

3.3.3. Hg in soil fractions

For combined sandy and clayey soil surface values, Hg transfer from finer to coarser particles seemed to have occurred following deforestation. Indeed, a significant loss of Hg in fp was observed ($p < 0.0003$, ds/fs = 0.92), whereas there was an increase of Hg associated to medium ($p < 0.0347$, ds/fs = 1.14) and coarse ($p < 0.0180$, ds/fs = 1.31) particles (Fig. 6). The same Hg dynamics existed when distinguishing for soil texture. Hg displacement between soil fractions was less pronounced in deeper horizons; at 20–25 cm, significant changes in Hg were only measured on the coarse fraction. Globally, at clayey and sandy sites surface horizons, about 25% on the Hg initially found in fine fraction was lost following slash-and-burn cultivation.

3.3.4. Cations and minerals

Surface soils were characterized by an important increase in base cations following slash-and-burn cultivation (Fig. 7). The enrichment

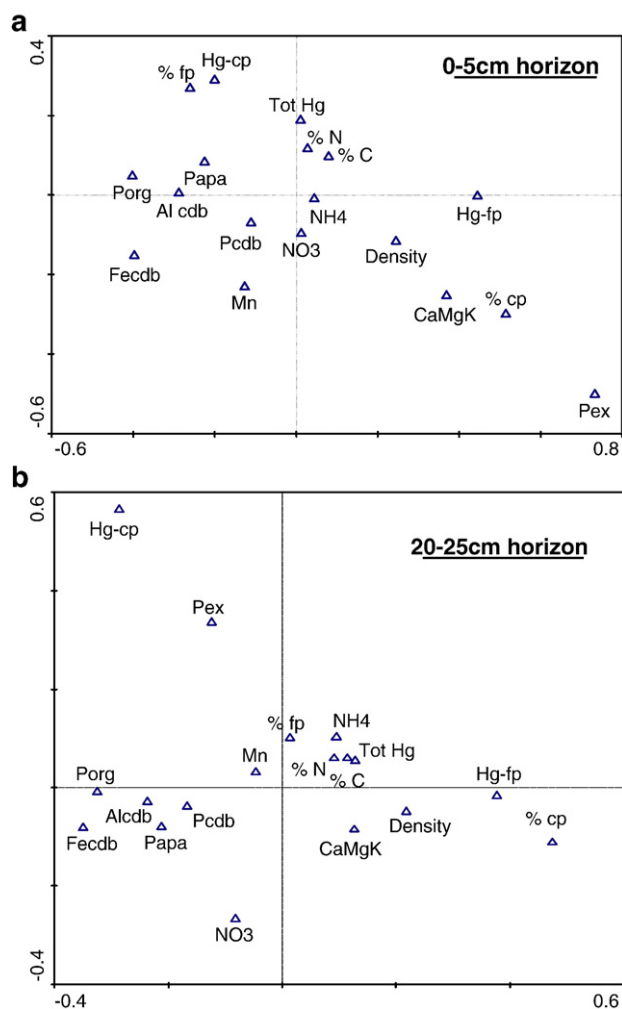


Fig. 4. Correspondence analyses of soil variables for combined sandy and clayey samples and values before and after disturbance.

¹ All subsequent statistical analyses comparing forest and deforested means of a given variable will be results of paired t -tests.

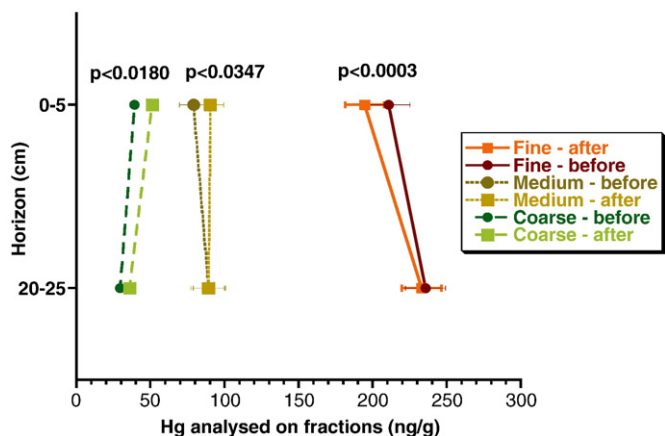


Fig. 6. Changes of Hg on soil granulometric fractions upon deforestation and a 1-year cultivation period, for combined sandy and clay soil samples. * $p < 0.05$ values (paired t -test results) indicate that there is a significant Hg change for a given soil fraction at the 0–5 cm horizon. * Error bars represent the standard deviation (SD).

was especially marked for surface clayey soils, as cations went from 0.83 to 1.62 cmol/kg (ds/fs ratio of 1.96). In sandy sites, cations went from 1.12 to 1.73 cmol/kg (ds/fs ratio of 1.54) (Table 1). Finally, Al_{cdb} and Fe_{ecdb} levels almost always decreased following slash-and-burn cultivation and the changes were more marked in deeper soils than at the soil surface. Although the changes were overall not particularly noticeable, the Fe_{ecdb} and Al_{db} losses were respectively significant in sandy and clayey sites subsurface (Fig. 8).

4. Discussion

4.1. Loss of fine particles

The present study took place in a region considered as moderately stable to vulnerable to erosion (Embrapa Amazônia Oriental, 2007d). Our samples indeed underwent a marked loss of fine particles following slash-and-burn cultivation, which indicates that erosion processes are already active within the first year after deforestation. Since soil fine fraction plays a key role in aggregation complexes, loss of fine particles has important impacts on soil structure and can lead to compaction and density increase (Brady and Weil, 2002), as observed in our results.

4.2. Total Hg retention

An important point that arises from this study is that the first year of slash-and-burn cultivation did not lead to a massive Hg movement out of our recently deforested tropical soils. The same thing was found by Engle et al. (2006) for temperate soils.

The total Hg burden (ng/cm^3) reflects the actual Hg dynamics better than Hg concentration (ng/g) as it takes into account eventual soil density changes. By comparing the Hg burden ds/fs ratio with the Hg concentration ds/fs ratio, we observed that Hg burden changes were greater than Hg concentration changes in both types of soils. This indicates that the increase of Hg burdens could be attributed to the soil density increase occurring following slash-and-burn.

The response of physico-chemical variables to slash-and-burn cultivation and Hg dynamics differed according to soil texture. In clayey sites, Hg burdens and density both increased of about 5–6% at soil surface after burn (ds/fs ratios of 1.05 and 1.06 respectively), reinforcing the assumption that for this type of soil, the observed Hg increase was related to density increase.

However, density changes were not as marked in sandy sites than in clayey sites. In sandy sites, the Hg burden increase (18%) was more important than the density increase (4%). Furthermore, Hg increase could not be attributed to a density increase, because it was also observed when looking at Hg concentration (ng/g). Since soils often undergo a significant fine particle erosion upon slash-and-burn (Alfaia et al., 2004; McGrath et al., 2001; Müller et al., 2004; Numata et al., 2007) and since Hg dynamics is related to soil Al and Fe-enriched fine fraction (Fadini and Jardim, 2001; Roulet and Lucotte, 1995) the analysis of Hg distribution in soil fractions and of erosion dynamics could provide an explanation for the surprising Hg increase observed in sandy soils. Interestingly, fine particles of sandy soils contained more Hg than clayey soils fine particles (even before disturbance), suggesting that the scarcer adsorption sites of sandy soils were more readily saturated. For deforested sandy sites, the perceived increase in total soil Hg resulted from a shift in Hg distribution between soil fractions as well as from a change in soil texture.

4.3. Early Hg mobility

Even though total Hg variations were not major in our study, early signs of Hg mobility were observed during the first year following slash-and-burn. Our results, like previous studies (Farella et al., 2006; Roulet et al., 1998), have shown that Hg was mostly associated with the soil fine fraction. Thus, marked fine particle loss such as what we

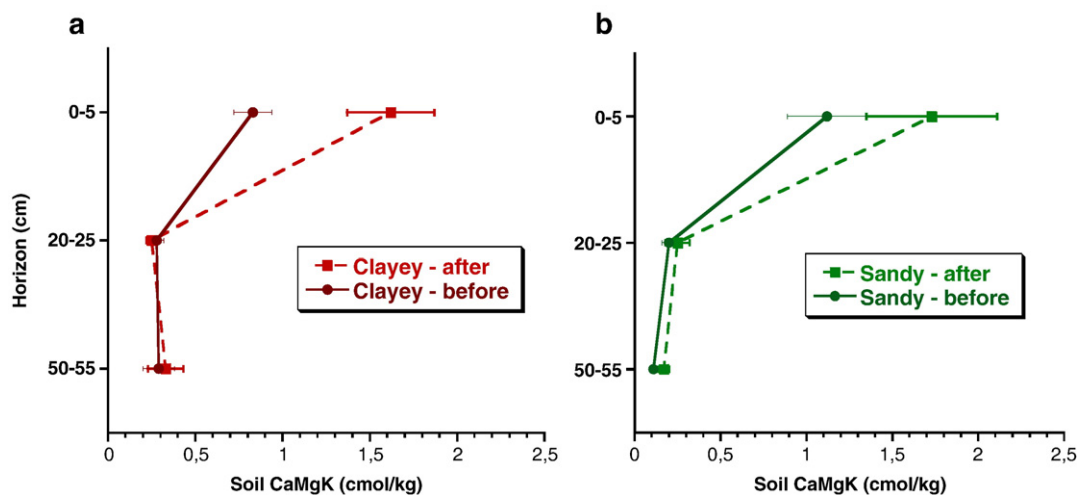


Fig. 7. Changes in soil sum of bases (CaMgK) in relation to depth upon deforestation and a 1-year cultivation period for two soil textures. a) Change in CaMgK in clayey soils b) Change in CaMgK in sandy soils. * Error bars represent the standard deviation (SD).

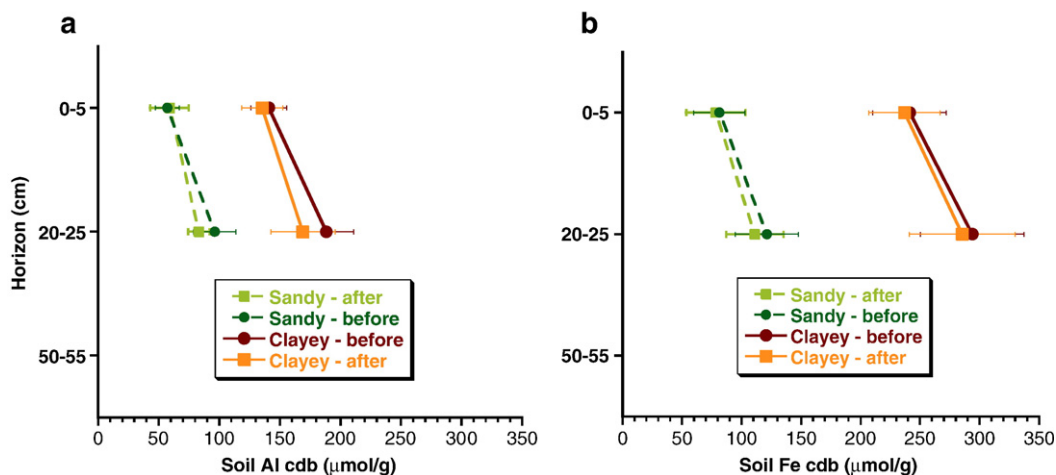


Fig. 8. Changes in soil Fe_{cdB} and Al_{cdB} in relation to depth upon deforestation and a 1-year cultivation period for two soil textures. a) Al_{cdB} in clayey and sandy soils b) Fe_{cdB} in clayey and sandy soils. * Error bars represent the standard deviation (SD).

observed has impacts on soil Hg levels (Roulet et al., 1998). Indeed, the lack of forest cover, agricultural activities and high precipitation favour the erosion of fine particles – and of their associated Hg content –, towards nearby waters (Maurice-Bourgoin et al., 2003). However, in addition to the loss of Hg through erosion processes, we measured as well a loss of Hg on fine particles, and an increase of Hg on medium and coarse particles, indicating a net Hg transfer (from fine to coarser particles) during the first year following slash-and-burn.

Our results did not show a marked Hg loss such as other studies previously found (Almeida et al., 2005; Farella et al., 2006; Lacerda et al., 2004; Roulet et al., 1998). Even if Hg loss is probably not yet occurring in recently deforested soils, we observed that Hg disequilibrium already existed after the first year of slash-and-burn cultivation. Indeed, after having been displaced from the soil fine fraction, Hg seemed to be still retained at least temporarily on larger soil particles. However, medium and coarse fractions – composed of various sizes of sand particles – are relatively less reactive (Brady and Weil, 2002) and have fewer adsorption sites. As Hg may be linked to these particles with weak chemical bonds, Hg mobility will probably be accentuated in further stages beyond the first year of cultivation.

4.4. Relationships between cation enrichment and Hg distribution

According to Farella et al. (2006), the act of burning is of primary importance for soil Hg release. Their research suggested that Hg mobility could result from a soil destabilisation that was triggered by massive cation enrichment. The Hg dislocation observed in our study after the first year of slash-and-burn cultivation reinforces this assumption. Furthermore, similar chemical competition could also be partly responsible for marked NH₄ loss observed in our slash-and-burn sites (Béliveau, 2008; Farella et al., 2007). In newly cleared lands, a rapid and massive cation enrichment results from nutrient-rich ash deposition at soil surface after the burning of the forest (Béliveau, 2008; Desjardins et al., 2000; Farella et al., 2007; Hölsher et al., 1997; McGrath et al., 2001; Markewitz et al., 2004; Müller et al., 2004; Da Silva et al., 2006; Wick et al., 2005). The cationic enrichment was more important in clayey than in sandy soils, which was probably related to relatively low initial cations values for clayey soils as well as to their high capacity to retain nutrients. In our study, the change in cation levels were not as pronounced as what previous authors observed over longer time-periods after deforestation (Farella et al., 2006). While Farella and colleagues found a 5.5-fold and a 4-fold cation increase in clayey and in sandy soil surface horizons, the cation increase in our samples were respectively 1.96 and 1.54, one year after deforestation.

Base cation fertilization is one of the desired effects of slash-and-burn practices, which is precisely the reason why it is frequently applied in the humid tropics for cultivation on poor acid soils (Farella, 2005). However, some studies carried out in Finland have suggested that an enhanced fertilization could lead to increased soil Hg mobility (Matilainen et al., 2001). In our study sites, the mean fertilization resulting from the biomass burning was about 0 g/m² of K, 3 g/m² of Mg and 14 g/m² of Ca in clayey soils and 0.26 g/m² of K, 2 g/m² of Mg and 13 g/m² of Ca in sandy soils (for more details about the calculation of fertilization effect, see Béliveau, 2008). Our study presented a total fertilization (CaMgK) that was much lower than those found in previous studies. Indeed, while the CaMgK enrichment was overall around 15 g/m² over our 150 km sampling region, there was an input of about 96 g/m² CaMgK in sandy soils of farms of the Brasilia Legal area (Farella et al., 2006), and of about 56 g/m² CaMgK in experimental Finnish sandy soils (Matilainen et al., 2001). The moderately low fertilization measured in our studied sites could have played a role in the relatively weak Hg mobilisation observed in our samples.

5. Conclusion

Our unique sampling design, consisting in soil collection at the exact same sites before disturbance of primary forests and one year after their initial slash-and-burn, allowed a precise analysis of Hg dynamics in recently deforested soils. Our results indicate that the first year of slash-and-burn cultivation was not responsible for a rapid and massive release of soil mercury to nearby aquatic systems. However, early signs of Hg mobility were detected. Indeed, the transfer of Hg from fine to coarser fractions that was observed after the first year of slash-and-burn cultivation probably resulted from a rupture of Hg chemical bonds on clay adsorption sites. Moreover, this process seemed to be related to competition between newly deposited cations and Hg. This early Hg mobility suggests an eventual Hg release in surrounding rivers, which would affect the Amazonian population and environment.

Our results have important implications for Amazonian farmers and land-use decisions. Given the loss of fine particles and the early mobility of Hg occurring within the very first year of slash-and-burn cultivation, concrete actions are needed in order to find solutions that would help to reduce the need of small-scale farmers to burn their land continuously, favouring soil erosion and fuelling Hg liberation towards aquatic systems. Furthermore, since soil Hg and physico-chemical properties dynamics are related to soil texture, our research reaffirms the importance of taking into account soil type in decisions

regarding land management. However, since slash-and-burn agriculture is one of the most common methods used by family farmers in the Amazon, projects have to consider the local reality of Amazonian populations, keeping in mind that slash-and-burn is a traditional activity that has become deeply incorporated in the customs of local communities. This method had been used in the region for centuries by native peoples before having been adopted by new settlers. Family farmers ensure their subsistence with very limited resources and slashing and burning is for them the preferred method to create low-cost agricultural systems.

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