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Mercury loss from soils following conversion from forest to pasture in Rondônia, Western Amazon, Brazil

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Deforestation can be responsible for maintaining high Hg levels in the Amazon environment, through a grasshopper effect of Hg remobilization from the affected soils.

Abstract

This work reports on the effect of land use change on Hg distribution in Amazon soils. It provides a comparison among Hg concentrations and distribution along soil profiles under different land use categories; primary tropical forest, slashed forest prior to burning, a 1-year silviculture plot planted after 4 years of forest removal and a 5-year-old pasture plot. Mercury concentrations were highest in deeper (60–80 cm) layers in all four plots. Forest soils showed the highest Hg concentrations, ranging from 128 ng g^{-1} at the soil surface to 150 ng g^{-1} at 60–80 cm of depth. Lower concentrations were found in pasture soils, ranging from 69 ng g^{-1} at the topsoil to 135 ng g^{-1} at 60–80 cm of depth. Slashed and silviculture soils showed intermediate concentrations. Differences among plots of different soil-use categories decreased with soil depth, being non-significant below 60 cm of depth. Mercury burdens were only statistically significantly different between pasture and forest soils at the topsoil, due to the large variability of concentrations. Consequently, estimated Hg losses were only significant between these two land use categories, and only for the surface layers. Estimated Hg loss due to forest conversion to pasture ranged from 8.5 mg m^{-2} to 18.5 mg m^{-2}, for the first 20 cm of the soil profile. Mercury loss was comparable to loss rates estimated for other Amazon sites and seems to be directly related to Hg concentrations present in soils.

Keywords: Amazon forest; Land use change; Pasture; Silviculture; Soils Hg burdens

1. Introduction

The increasing conversion of natural ecosystems for agricultural purposes is an important component of global environmental change, particularly in the Brazilian Amazon, where slashing and burning of natural tropical forests is a common and periodic practice performed by ranchers and farmers (Cordeiro et al., 2002). Tropical soils, in particular, are strongly affected by forest conversion (Feigl et al., 1995; Moraes et al., 1996; Herpin et al., 2002). In the Amazon Region the natural degradation of latosols as a consequence of the high humidity is a slow process, but it can be dramatically intensified by human intervention (Oliveira et al., 2001). The conversion of tropical forests into pasture and/or agricultural use is considered the main

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cause of accelerated leaching of nutrients and trace metals accumulated in Amazon soils. Studies on the consequences of deforestation and pasture establishment on soil chemical and physical properties (Moraes et al., 1996; Herpin et al., 2002) showed, in general, an increase of soil element concentrations, decreasing organic matter content and an increase in pH. Also, deforestation and agricultural practices affect pedological equilibrium giving rise to intense leaching and erosion.

Mercury is considered the element of most environmental concern in the Amazon Region. Silver and gold mining during colonial times, present gold prospecting and relatively high natural Hg concentrations in Amazon soils, have resulted in a general contamination throughout the region (Lacerda and Salomons, 1998; Lacerda, 2003). However, the consequences of land use change on Hg remobilization from Amazon soils have been the subject of only a few studies. Roulet et al. (1999) suggested that deforestation was responsible for increasing Hg transport through the Tapajós River, Eastern Amazon. Fostier et al. (2000) estimated a doubling of Hg loss to rivers after forest conversion to pasture in an Amapá State watershed, Northern Amazon. Lacerda (1995) estimated a net Hg loss due to forest burning of 7.8 g ha^{-1} $year^{-1}$ during the last decade of the 20th century, assuming average deforestation rates of about 13,000 km^2 $year^{-1}$. Godoy et al. (2002) and Cordeiro et al. (2002), based on Hg distribution in dated lake sediment cores, reported an increase in Hg deposition in lake sediments from the Pantanal and Alta Floresta, Southern Amazon, associated with increasing soil erosion due to agriculture and road construction, respectively. Preliminary results obtained in Rondônia, Western Amazon, also showed the effect of deforestation on Hg degassing rates with pasture soils showing degassing rates of 46.5 ± 10.7 ng m^{-2} h^{-1}, about six-times higher than in forest soils (8.4 ± 1.2 ng m^{-2} h^{-1}) (Almeida et al., 2004). As a result, Hg concentrations tend to be lower in pasture compared to forest soils (Lacerda et al., 2004). Therefore, land use changes are expected to mobilize Hg present in soils and in the forest biomass and re-emit it to the atmosphere either as vapor or associated with particles, and to surface waters associated with higher erosion fluxes. To what depth in the soil column these processes take place is still unknown, as well as the time required for building up the former Hg concentrations of the original soil. Therefore, to increase the understanding of the effect of land use change on Hg distribution in Amazon soils, this work provides a comparison among Hg concentrations and distribution along the soil profile under different land use categories; primary tropical forest, slashed forest prior to burning, a 1-year silviculture plot planted after 4 years of forest removal and a 5-year old pasture plot, located in the Madeira River basin, Rondônia State, western Amazon region in Brazil.

2. Material and methods

2.1. Study area

The upper Madeira River basin was the second most important gold prospecting area in the Amazon region during the last two decades of the past century. The "gold rush" in the Madeira River started in 1975 as a non-mechanical activity, mostly on river margins and sand banks during the dry season. This was rapidly followed by the use of boats and divers and then followed by mechanical dredges, to the extent that in 1985, 1500 pieces of equipment, 800 of them being large mechanical dredges, were working in the upper Madeira River, from the Bolivian border to the State Capital of Porto Velho, Rondônia. Production from this gold rush reached an annual average of 9.4 tons of gold; resulting in an average Hg emission to the environment of 12.4 tons $year^{-1}$, count about 87 tons between 1979 and 1986. About 40 tons were lost as metallic Hg to rivers while about 47 tons were lost to the atmosphere (Pfeiffer and Lacerda, 1988; Lacerda et al., 1989). Since deposition of atmospheric Hg in the region occurs within 40 to 60 km from sources (Lacerda et al., 2004), most of the Hg emitted to the atmosphere was probably deposited in soils along the river.

This study was carried out in the Candeias do Jamari, Rondônia State (Western Amazon basin). Deforestation in Rondônia State has been very intense, affecting an area of 58,504.38 km^2, or 24.45% of the total state area between 1996 and 2000. This represents about 10% of the total deforested area of the Amazon basin (Fernandes and Guimarães, 2002). The climate of Rondônia State is predominantly tropical, humid and hot year round, with insignificant annual thermal variations but notable diurnal thermal variations, especially during the winter. Rondônia State has an Aw weather type (Köppen classification) with annual rainfall varying from 1400 to 2300 mm and a short but well-defined dry season from June to August, when most forest burning occurs. The mean annual maximum and minimum temperatures range from 24.4 to 25.5 °C and 18.8 to 20.3 °C, respectively. The native forest vegetation is open humid upland tropical forest.

Samples were collected in four different plots in the Mata Verde farm, at the municipality of Candeias do Jamari, a 940-ha area, about 60 km south of the capital city of Porto Velho. The plots comprise 640 ha of undisturbed rainforest; 20 ha of slashed forest (cut in 2002), where the forest biomass was left on the soil for about one year; a 80-ha plot, slashed and burned in 1997

and presently occupied by a 1-year old "bandarra" (*Parlcia paraensisi*) plantation (the soil for the silviculture was mechanically plowed to about 60 cm depth); and 200 ha of a 5-year-old pasture, also created by slashing and burning. Fig. 1 shows the location of the study site and sampled plots.

2.2. Sampling and analysis

In each of the four plots, referred-to in following sections as forest, slashed, silviculture and pasture, two 80 cm soil profiles were collected in September 2001 and November 2002. In each sampling, two different profiles from each plot were sampled, count 4 profiles for each soil category. These profiles were taken using an auger after the manual removal of the litter and humus layers. In these profiles, soil layers were collected at 20 cm intervals up to 80 cm of depth.

All soil samples were stored in clean plastic bags and frozen no longer than 6 h after sampling. At the laboratory, 10 g of fresh soil from each sample was used for pH determination in 1:2.5 water slurry using a glass electrode (Feigl et al., 1995). Fresh soils were packed in pre-weighed small boxes (2 cm × 2 cm), dried and weighted again to determine dry densities. Sub-samples were dried at 50 °C for 24 h to constant weight for moisture determination. Dried samples were sieved (<1.0 mm) to eliminate roots and other plant debris and rock particles. Sub-samples were burned at 450 °C for 24 h for gravimetric estimation of organic matter content. The concentrations of Fe oxi-hydroxides (Fe_{oxi}) were determined after extraction using the citrate–dithionate–bicarbonate buffer method, by conventional flame atomic absorption spectrophotometry.

Mercury was extracted through digestion in 50% v/v *aqua regia* solution (2 g of dried soil in 20 mL of acid solution) following Aula et al. (1995) and analyzed by CVAAS in a Coleman Model MAS-50D Mercury Analyzer System. The accuracy of the Hg determination in soil samples was assessed by simultaneous analysis of certified reference material (NIST 1646a Estuarine Sediments, U.S. Department of Commerce, National Institute of Standards Technology) with a certified Hg concentration of 60 ng g^{-1}. These analyses gave Hg concentrations of 58 ± 3 ng g^{-1} ($n = 5$). Standard deviation among sub-samples at the same site were <15% and <10% for Fe_{oxi} and Hg concentrations, respectively, and <2% for organic matter content.

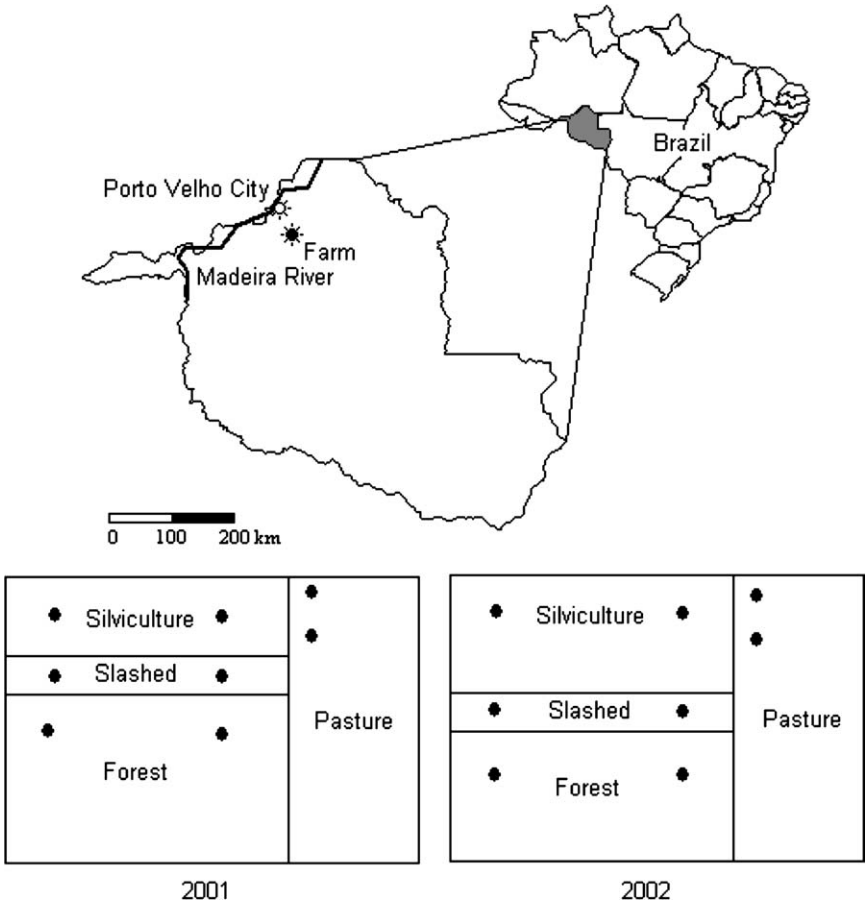

Fig. 1. Study sites at Candeias do Jamari, Rondônia State, Western Amazon.

3. Results and discussion

3.1. Mercury concentration in Candeias do Jamari profile soils

Table 1 shows mean and standard deviation of pH, moisture and organic matter content, and Fe_{oxi} and Hg concentrations measured in Candeias do Jamari in the four plots studied. Due to the large variability of the Hg concentrations measured in the studied soils and the relatively small sample size, non-parametric tests (Wald–Wolfowitz, Mann–Witney and Kolmogorov–Smirnov Test) were used to make the comparison between the averages from each layer within one profile, to evaluate differences between adjacent layers, and between profiles in different soil-use categories, in order to verify the effects of the cutting of the original vegetation. The differences were only considered significant when the three tests gave the same results with a level of significance of 5%.

There was no significant difference between adjacent layers in the same profile in organic matter and Fe_{oxi} contents in any of the soil-use categories, but a significant difference ($P < 0.05$) was found between the Fe_{oxi} and Hg concentrations in the surface and the deepest layer in forest soil profiles. The pH also presented a significant difference ($P < 0.05$) between the surface layer (0–20 cm) and the adjacent layer at 20–40 cm in forest soils. Similarly, moisture content differed significantly only between the layers 20–40 and 40–60 cm in the slashed forest plot.

Mercury concentrations increased with increasing depth in all soil profiles. Lower Hg concentrations found in the topsoil of the pasture plot suggest the impact of a stronger soil exposure. Other authors have also reported the pattern of increasing concentrations with depth found for Hg and Fe_{oxi}. Brabo et al. (2003) reported significantly lower Hg concentrations in the upper soil horizon (0–10 cm) compared to deeper layers (50–60 cm) in Pará State, Northeastern Amazon, whereas Roulet et al. (1998) found lower Hg and Fe concentrations in the topsoil relative to deeper layers in the same area. These authors proposed a surface release of Hg and Fe by leaching and accumulation in Fe-rich deeper horizons of soils. However, in the Tartarugalzinho River, Amapá State, Northern Amazon, results obtained from deeper soil profiles showed that this increase stops at the stone-line. Mercury concentrations of more than 100 ng g^{-1} were present above the stone-line, but decreased downward to 30 ng g^{-1} in the saprolite horizon (Oliveira et al., 2001). Unfortunately, there is no similar study in pasture soils to compare with our results.

The average Hg concentrations for the 80 cm profiles were higher in forest soils (135.7 ± 24.1 ng g^{-1}) followed by slashed (121.5 ± 21.3 ng g^{-1}), silviculture (102.8 ± 20.7 ng g^{-1}) and pasture (100.7 ± 25.7 ng g^{-1}). Average Hg concentrations were not significantly different (*t*-test, $P < 0.05$) between forest and slashed, as well as between silviculture and pasture. But the two group averages were significantly different.

The comparison between soils layers at the same depth, but in different soil-use categories (forest, slash forest, silviculture and pasture) presented clearer differences for most parameters, particularly in the topsoil. In general, these differences decreased with depth. pH presented a significant difference ($P < 0.05$) only between forest soils and pasture, but the differences occurred in three different layers (0–20, 20–40 and 60–80 cm). Organic matter and moisture contents seem

Table 1
Physical–chemical characteristics and Hg concentrations in forest, slashed, silviculture and pasture soils (yellow-red latosols, oxisols) from Candeias do Jamari, Rondônia State, Western Amazon

	Soil depth (cm)	pH	Moisture (%)	OM (%)	Fe_{oxi} (%)	Hg (ng g^{-1})
Forest	0–20	4.4 ± 0.0	21.3 ± 1.1	13.8 ± 0.8	2.4 ± 0.9	127.8 ± 18.7
	20–40	4.8 ± 0.1	21.9 ± 12.4	13.1 ± 1.5	2.0 ± 0.2	128.9 ± 38.6
	40–60	4.9 ± 0.3	21.0 ± 0.3	12.6 ± 0.5	2.2 ± 0.2	141.0 ± 18.0
	60–80	4.7 ± 0.1	20.9 ± 0.4	12.7 ± 0.5	2.1 ± 0.3	150.1 ± 17.1
Slashed	0–20	4.7 ± 0.6	22.2 ± 2.9	13.5 ± 2.8	1.7 ± 0.2	119.6 ± 12.1
	20–40	4.7 ± 0.3	23.4 ± 0.2	11.8 ± 1.6	1.8 ± 0.3	118.0 ± 17.2
	40–60	4.9 ± 0.2	22.9 ± 0.0	12.3 ± 2.9	2.3 ± 0.4	120.4 ± 38.8
	60–80	4.9 ± 0.2	22.8 ± 0.6	10.3 ± 2.2	1.9 ± 0.5	133.1 ± 15.4
Silviculture	0–20	4.7 ± 0.8	16.0 ± 4.9	11.2 ± 1.9	1.9 ± 0.5	94.0 ± 14.7
	20–40	4.7 ± 0.6	17.6 ± 3.4	11.6 ± 1.0	1.8 ± 0.8	112.4 ± 26.0
	40–60	4.8 ± 0.6	19.9 ± 0.9	10.9 ± 0.6	2.5 ± 0.9	111.0 ± 22.6
	60–80	4.9 ± 0.4	20.4 ± 1.0	10.5 ± 0.7	1.9 ± 0.8	109.5 ± 16.9
Pasture	0–20	5.7 ± 0.3	9.2 ± 0.4	5.2 ± 0.6	0.6 ± 0.1	68.9 ± 2.5
	20–40	5.5 ± 0.3	10.7 ± 0.1	5.1 ± 0.5	0.9 ± 0.4	90.5 ± 5.3
	40–60	5.4 ± 0.6	10.5 ± 0.1	5.0 ± 0.5	1.1 ± 0.2	112.8 ± 6.7
	60–80	5.5 ± 0.5	10.5 ± 0.6	4.7 ± 0.8	1.6 ± 0.2	135.2 ± 9.7

to be the parameters most sensitive to changes in land use, presenting the largest variations in relation to forest soils. Moisture and organic matter contents decreased significantly in the two deepest layers (40–60 and 60–80 cm) of the slashed forest soil. Silviculture soils showed significant differences in moisture content in the three first layers, whereas pasture and forest soils presented significant differences in all four. The concentrations of Fe_{oxi} were significantly higher in the forest plot than in the other soil-use categories, particularly pasture, for all sampled layers. Hg concentrations in the first layer of forest and slashed plots were higher than those measured in pasture and silviculture soils. But were not significantly different in the deepest layers of all four soil-use categories.

The greater impact of land use change on soil characteristics is shown by pasture soils. However, it is interesting to note the effect of land use change on the measured parameters is also exhibited, although to a lesser extent, by silviculture soils. In fact, the silviculture and pasture soils are the most changed relative to the original forest soil. These impacts, however, were only significantly different at the topsoil.

In the pasture soils, Hg concentrations exhibited a significant positive correlation ($P < 0.01$) with Fe_{oxi} concentrations. This result has been previously reported for other Amazon sites (Roulet et al., 1998, 1999, 2000). However, this correlation was not present in the other land use categories. Fe_{oxi} concentrations also showed a significant negative correlation ($P < 0.05$) with organic matter in the pasture soils. These correlations suggest that leaching of Hg followed Fe dynamics, as proposed by Roulet et al. (1998, 1999), and this is a key process controlling Hg mobility in Amazon soils.

The average Hg concentrations found in Candeias do Jamari soils are similar to those found in most other Amazon areas. Hg concentrations in all plots ranged from 67 to 176 ng g^{-1}, and exhibited the highest values in forest soils and lower values in pasture topsoil (Table 1). Similar results were reported for Alta Floresta, Southern Amazon by Lacerda et al. (2004). The observed concentrations in all soil samples were consistently higher in deeper layers in comparison to topsoil (Fig. 2). Hg concentrations in the surface of forest soils varied from 112 to 153 ng g^{-1}, and are comparable to the values measured in the surface of

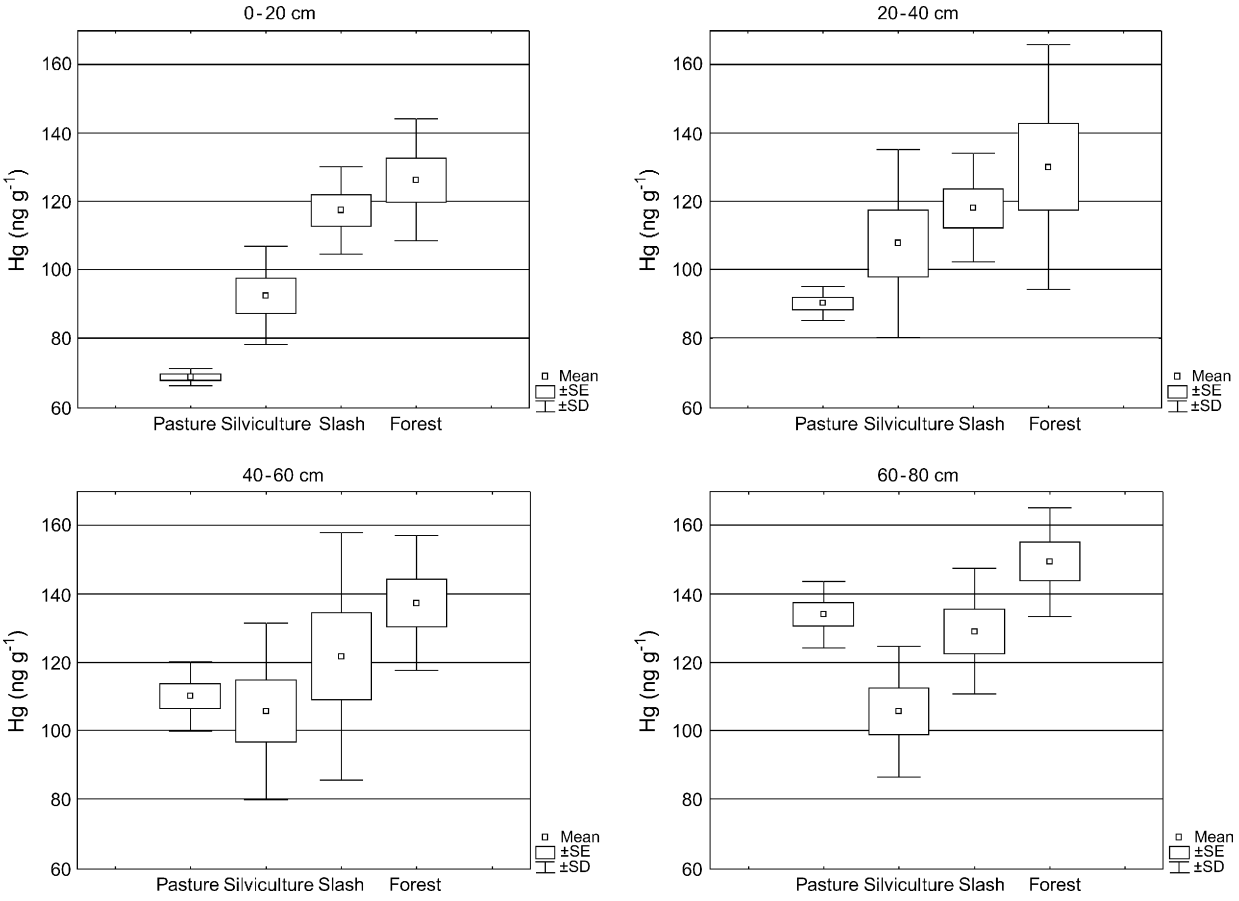

Fig. 2. Mean, standard deviation and standard error of soil mercury concentrations in different layers under different soil-use categories at Candeias do Jamari, Rondônia State, Western Amazon.

forest soils by other investigators working in the Amazon. Roulet et al. (1998) found forest soils Hg concentrations varying from 44 to 103 ng g^{-1} in the Tapajos River basin, and Zeidemann and Forsberg (1996) found values ranging from 50 to 170 ng g^{-1} in the Rio Negro basin. However, our values were lower than those reported for the lower Madeira River basin (232 to 406 ng g^{-1}, Lechler et al., 2000) and for the Serra do Navio watershed (Amapa) where topsoil (0–10 cm) of natural forests showed average Hg concentration of 304 ± 62 ng g^{-1} (Fostier et al., 2000). On other hand, the values reported by Lacerda et al. (2004) in Alta Floresta, Southern Amazon (61.9 ± 50.6 ng g^{-1}) were lower than the Hg concentrations found in this work. The lowest Hg concentrations reported in this study were found in the surface of pasture soils (68.9 ± 2.5 ng g^{-1}), but Lacerda et al. (2004) reported even lower Hg concentrations in pasture surface soils in Alta Floresta, Southern Amazon (33.8 ± 13.9 ng g^{-1}). Nevertheless it is very difficult to compare these concentrations because they depend on pasture age and maintenance, and there is no similar study on Hg concentrations in Amazon pasture soils available in the literature.

3.2. Mercury burdens in Rondônia soils

Table 2 exhibits cumulative Hg burden in mg m^{-2} and percentage of the total profile burden by layer for each of the four different soil-use categories. In forest, slashed and pasture soils the highest percentage of the total Hg burden by layer was found in the deeper layers (28%, 27% and 35%, respectively, at 60–80 cm layer), while in silviculture soils the highest percentage of the total Hg burden by layer was found in the 20–40 cm layer. This result is probably due to the mechanical plowing of the soil prior to planting the "bandarra" trees. As expected, the highest cumulative Hg burden to the entire 80 cm profile occurred in forest soils (156 ± 24 mg m^{-2}), followed by slashed (139 ± 14 mg m^{-2}), silviculture (118 ± 13 mg m^{-2}) and pasture (116 ± 6 mg m^{-2}). Cumulative Hg burdens from Candeias do Jamari soils compare well with Yellow oxisols from French Guiana (63–69 mg m^{-2} of 0–20 cm; Roulet and Lucotte, 1995) and the Tapajós basin (84–181 mg m^{-2} of 0–60 cm; Roulet et al., 1998); and with Ultisols from the Tocantins River basin (76 mg m^{-2} of 0–60 cm; Aula et al., 1994) and the Tapajós basin (42–97 mg m^{-2} of 0–60 cm; Roulet et al., 1998).

Table 2
Cumulative Hg burden in mg m^{-2} and % by layer in forest, slashed, silviculture and pasture soils from Candeias do Jamari, Rondônia State, Western Amazon

Depth (cm)	Cumulative Burden (mg m^{-2})	% by layer	Cumulative Burden (mg m^{-2})	% by layer
	Forest		Pasture	
0–20	31.3 ± 4.7	20.1	17.9 ± 1.9	15.4
0–40	69.5 ± 11.8	24.5	43.8 ± 2.7	22.3
0–60	111.6 ± 13.4	27.0	75.7 ± 5.2	27.4
0–80	155.8 ± 14.4	28.4	116.5 ± 6.5	35.0
	Silviculture		Slashed	
0–20	24.4 ± 4.3	20.7	30.7 ± 4.1	22.2
0–40	56.3 ± 8.8	27.1	65.4 ± 6.9	25.0
0–60	86.7 ± 12.0	25.8	101.7 ± 13.1	26.2
0–80	117.7 ± 13.1	26.4	138.6 ± 14.4	26.6

Cumulative Hg burden in forest soils was much higher than in pasture soils (up to 1.7 times higher at 0–20 cm layer), but this difference decreased with depth. The largest difference in Hg content between pasture and forest soils occurred at the topsoil. The much smaller Hg burdens in pasture soils suggest strong Hg losses either through stronger erosion (Fostier et al., 2000) and/or degassing (Lacerda et al., 2004; Almeida et al., 2004). Below the pasture topsoil a gradual increase in concentration and burden occur, showing that the effect of forest conversion to pasture affects in particular, the first 20 cm of the soil. Hg burdens in deeper layers were not significantly ($P < 0.05$) different from forest soil Hg burdens. Silviculture and slashed soil plots show an intermediate pattern of Hg burden distribution relative to forest and pasture soils (Fig. 1 and Table 2). Nevertheless, the difference relative to forest soils was not significantly different ($P < 0.05$).

Since no statistical significant difference between silviculture and slashed soils relative to forest soils was found, Hg losses due to land use change could not be estimated for these soil-use categories. The loss of soil Hg can only be estimated by comparison between forest and pasture for the first 20 cm layer, where statistical differences could be detected. Friedli et al. (2003) measured Hg emission factors for forest fires in the laboratory and in the field ($14–71 \times 10^{-6}$ and 112×10^{-6} g Hg kg^{-1} (dry mass), respectively), they believed that this difference might be due to the contribution of Hg released from the fire-heated soil under field conditions, which would be stopped after the extinction of the fire, at least at relatively deeper layers, resulting in a relatively shallow impact on the Hg present in deeper layers. The magnitude of Hg loss per unit of area (Table 3) found for these Candeias do Jamari soils (0–20 cm) varied from 8.3 to 18.5 mg m^{-2}, being in the range found for a few other studies the Amazon region. For example, Lacerda et al. (2004) estimated bulk Hg loss after forest conversion to pasture in southern Amazon lowland forests, with average surface Hg concentrations of 66 ng g^{-1}, to reach 3.4 mg m^{-2}. Fostier et al. (2000) estimated Hg loss from a northeastern Amazon, with average forest soils mercury concentrations of 304 ng g^{-1}, to reach up to 28 mg m^{-2}. This suggests that processes

Table 3
Mercury release in mg m^{-2} and % by layer in slashed, silviculture and pasture soils relative to forest soils from Candeias do Jamari, Rondônia State, Western Amazon

Depth (cm)	Release (mg m^{-2})	% layer	Release (mg m^{-2})	% by layer	Release (mg m^{-2})	% layer
	Forest–Pasture		Forest–Slashed*		Forest–Silviculture*	
0–20	13.4 ± 5.1	34.1	0.6 ± 6.3	3.2	6.9 ± 6.4	18.2
0–40	25.7 ± 12.1	31.2	4.1 ± 13.6	20.6	13.3 ± 14.7	16.7
0–60	35.8 ± 14.3	25.8	9.9 ± 18.7	33.6	24.9 ± 18.0	30.5
0–80	39.3 ± 15.8	8.9	17.2 ± 20.3	42.7	38.1 ± 19.4	34.6

*No statistical difference ($P < 0.05$).

controlling Hg loss from soils after forest conversion to pastures are probably very similar, but may vary up to one order of magnitude depending on Hg soil concentrations.

The results presented here show that deforestation can be responsible for maintaining high Hg levels in the Amazon environment, through a grasshopper effect of Hg remobilization from the affected soils. The profiles of Hg concentrations in the Candeias do Jamari soils suggest stronger Hg leaching and more intensive degassing to the atmosphere at the topsoil, after conversion. Below the topsoil a gradual increase in concentrations and burdens occur, showing that the effect of forest conversion to pasture affects only the surface layers of the soil. As deforestation rates in the Amazon region nearly doubled during the first years of the present century, reaching about 23,000 km^2, while gold mining has significantly decreased, land use change is today the most important mechanism of maintaining high Hg content in most Amazonian environments.

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