The effects of land use change on mercury distribution in soils of Alta Floresta, Southern Amazon

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"Capsule": *Land use change is a strong re-mobilizing agent of Hg distribution in Amazon soils.*

Abstract

This study presents the spatial distribution, degree of contamination and storage capacity of Hg in surface forest and pasture soils from Alta Floresta, Southern Amazon, a significant gold mining site from 1980 to 1996. During that period, average annual gold production was about 6.5 tons, with an estimated Hg annual emission to the environment of about 8.8 tons, 60–80% of it being emitted to the atmosphere. Mercury sources to the region are mining sites and gold-dealer shops at the city of Alta Floresta, where gold is smelted and commercialized. Mercury concentrations in forest soils (15–248 ng g^{-1}, average = 61.9 ng g^{-1}) were 1.5–3.0 times higher than in pasture soils (10–74 ng g^{-1}, average = 33.8 ng g^{-1}), suggesting strong re-mobilization after deforestation. Highest Hg concentrations were found within a distance of 20–30 km from mining sites in both soil types. The influence of the refining operations within the city of Alta Floresta, however, was less clear. Somewhat higher concentrations were observed only within a 5 km radius from the city center where gold-dealer shops are located. Wind direction controls the spatial distribution of Hg. Background concentrations (15–50 ng g^{-1}) were generally found at the outer perimeter of the sampling grid, about 40 km from sources. This suggests that Hg released from mining and refining activities undergoes rapid deposition. Estimated cumulative Hg burdens for the first 10 cm of soil averaged 8.3 mg m^{-2} and 4.9 mg m^{-2}, for forest and pasture soils respectively and compare well with ultisols and hydromorphic oxisols, but were lower than those found in yellow-red and yellow latosols and podsols from other Amazonian areas. Our results show that changing land use in the Amazon is a strong re-mobilizing agent of Hg deposited on soils from the atmosphere.
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1. Introduction

Mercury emissions and atmospheric deposition to the Amazon region has increased significantly, due to gold mining, during the last 3 decades. About 60–80% of the yearly Hg consumption in small-scale gold mining (60–100 t year^{-1}, from 1985 to 1991) was emitted to the atmosphere during the burning of the Au-Hg amalgam and gold smelting (Pfeiffer and Lacerda, 1988; Lacerda, 1997). This input is about 10 times higher than forest burning, the other major anthropogenic source of Hg to the region (Lacerda, 1995). Average background regional atmospheric deposition rates during the Holocene,

estimated from dated sediment cores from remote Amazon lakes, varied from an average of 2.8 µg m^{-2} year^{-1} prior to the Last Glacial Maximum (LGM) to 8.6 µg m^{-2} year^{-1} after the LGM (Santos et al., 2001) reflecting changes in aridity and vegetation cover during the Holocene (Sanaiotti et al., 2002; Turcq et al., 1998; Pessenda et al., 1998a). Atmospheric deposition of Hg increased to 7.0–9.0 µg m^{-2} year^{-1} during colonial times (Lacerda et al., 1999), probably reflecting the large Hg emissions from Spanish silver mines (Nriagu, 1994; Camargo, 2002). During the past 30 years, deposition rates increased to 10–16 µg m^{-2} year^{-1} (Lacerda et al., 1999) and to 18.2–20.3 µg m^{-2} year^{-1} (Fadini and Jardim, 2001), as a response to the gold rush (Lacerda and Salomons, 1998) and human occupation and land use change in the region (Cordeiro et al., 2002). In areas

under direct influence of gold mining, however, Hg atmospheric deposition may range from 60 to 120 μg m^{-2} year^{-1} (Lacerda et al., 1991a; Leady and Gottgens, 2001) and reach extreme values of up to 510 μg m^{-2} year^{-1}, and significantly correlate with gold production figures (Cordeiro et al., 2002).

A major sink of atmospheric Hg is the soil (Iverfeldt, 1991; Haygarth and Jones, 1992), although most studies on the distribution and biogeochemistry of Hg in Amazon soils are generally local, considering the 6 million km^2 of the Amazon basin, recent studies have confirmed the importance of this compartment to understand the Hg cycle in the Amazon region (Oliveira et al., 2001). The fate of Hg in forest and agriculture/pasture areas was studied in French Guyana (Roulet and Lucotte, 1995), around the Tucurui Reservoir, Para State (Aula et al., 1994, 1995), along the Tapajos River basin (Roulet et al., 1998, 1999, 2000) along the Negro River basin, central Amazon (Silva-Forsberg et al., 1999; Fadini and Jardim, 2001), at the Serra do Navio area in Amapa, northern Amazon (Gonçalves et al., 1998; Fostier et al., 2000) and along the Madeira River course, western Amazon (Lechler et al., 2000). Mercury concentrations reported in these studies varied widely from 40 to 400 μg g^{-1}. Some restricted studies also dealt with urban soils close to gold dealer shops (Malm, 1993; Rodrigues and Maddock, 1997), or to soils directly affected by mine tailings (Shrestha and Quilarque, 1989; Lacerda et al., 1991a,b), these studies showed much higher Hg concentrations, from one to two orders of magnitude higher than those reported for forest soils.

Most of these studies showed large variability in Hg concentrations depending on the watershed analyzed and on the soil type. For areas directly affected by small-scale gold mining activities concentrations are very high, suggesting a short residence time of the Hg emitted to the atmosphere, and low mobility of the Hg released with mine tailings (Lacerda and Salomons, 1998). Forest soils far from Hg point sources showed lower but also highly variable Hg concentrations (14–320 μg g^{-1}, Roulet et al., 1998). In general, Hg accumulates in Amazon soils either at the surface organic layer (Gonçalves et al., 1998), generally associated with atmospheric deposition (Fostier et al., 2000); and/or in the mineral horizons along the soil column generally associated with accumulation horizons of iron and aluminum oxides (Roulet et al., 1998; Oliveira et al., 2001). Therefore, Hg is capable of being mobilized due to the oxidation of the overlaying soil organic matter and the degradation of the iron duricrusts. Both processes are accelerated by deforestation and changes in land use, as has been shown at least for the Amapa region (Oliveira et al., 2001; Fostier et al., 2000) and the Tapajos River valley (Roulet et al., 1998, 1999). The present paper compares the distribution of Hg in surface forest and pasture soils of a large area (ca. 8000 km^2) around Alta Floresta, Mato Grosso State, a major mining site in the southern Amazon, to the effects of local Hg sources and of land use changes on the lateral distribution of Hg concentrations and the total Hg burden in such soils.

2. Material and methods

2.1. Study area

Alta Floresta, Mato Grosso State, southern Amazon, is a major gold mining area in the Brazilian Amazon. The region produced over 90 tons of gold from 1980 to 1996, with an estimated Hg emission ranging from 1 to 12 t year^{-1}, with an average of 8.8 t year^{-1} (Hacon et al., 1995; Maron, 1999). After 1994 gold production became negligible (Fig. 1) due to complete exhaustion of easily-mined placer deposits and improving of socio-economic conditions (Cordeiro et al., 2002). However, about 140 t of Hg have been left behind from this gold rush. Mercury sources in the region were from the prospecting and mining sites proper, located in rural areas where gold is amalgamated and the amalgam burned in open air; and from gold dealer shops, where gold with about 5–10% of Hg impurity is smelted and Hg is emitted to the urban area of Alta Floresta. Alta Floresta has also been an important colonization center for the southern Amazon leading to intense deforestation which resulted in a patchy landscape with a mixture of pristine tropical forests, perennial and annual agriculture fields and pasture lands. Slash and burn of forested areas is the common practice of local ranchers and farmers preparing the land for agriculture and cattle pasture. Deforestation starts in August, later dry season, and is followed by burning of the slashed biomass. Gold mining also peaked during the dry season (Cordeiro et al., 2002).

The regional climate is warm, humid tropical with annual temperature varying from 23 to 37 °C and annual rainfall of about 1800 mm distributed in a rainy season from September to April and a strong dry season
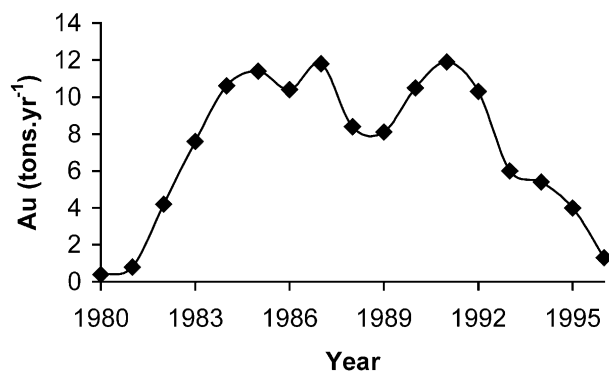

Fig. 1. Gold production at Alta Floresta region from 1982 to 1996, based on estimates by Hacon (1996).

from May to August. Dominant original vegetation cover is the dense "Terra-firme" forest, which still covers significant sectors of the region (Nogueira and Oliveira, 1983). The region is part of the Central Brazilian Crystalline Plateau, formed by Proterozoic terrain (1800–1100 Ma) formed by intermediate-acid volcanic bedrock and scattered granite stocks. Local soils are red- yellow latosols (leached ferralitic soils, oxisols), about 3 m deep with scattered flooded areas with highly leached hydromorphic soils (mineral hydromorphic gley soils) of the same origin (RADAMBRASIL, 1980; Young, 1976).

2.2. Sampling and analysis

Surface soils were collected in 31 sites along two axes. A first axis (NE–SW) following the dominant wind direction (60%) starting near the Cristalino mining area and the Arosto Island; a second axis (SE–NW) started near Peixoto de Azevedo mining area, following the second most dominant (30%) wind direction. Both axes crossed the urban area of Alta Floresta city. Total sampled area covered approximately 8000 km^2, located between latitudes 9°38′ and 10°07′ S and longitudes 55°46′ and 56°19′ W (Fig. 2). Each sampling site

consisted of a forest area adjacent to a pasture area, allowing sampling at the same relative distance from any Hg sources for each pair of samples, but under different vegetation cover. Care was taken to collect the samples at least 5 km from the nearest mining site, in order to avoid direct Hg contamination from mine tailings or accidental spills. All sampling stations were on flat ground in undisturbed vegetation well away from the ecotone (forest/pasture) and from roads and creeks.

Five to ten soil samples were collected from a 20×20 m plot in each station, after the removal of the leaf litter layer, which may not integrate atmospheric deposition over long periods of time, and are very variable in depth and composition depending on site. Small trenches to 30 cm of depth were dug and samples were collected using a plastic shovel laterally between 0 and 2 cm of depth, and from 8 to 10 cm depth, roughly corresponding to the organic layer. At six selected sites in forest areas soil cores were taken using a 4 m auger to study the vertical distribution of Hg to the bottom of the soil pit. In these cores samples were collected at 20 cm intervals to the first meter and 50 cm intervals to the bottom of the core.

All soil samples were stored in clean plastic bags and frozen no longer than 6 h after sampling. At the laboratory, samples were air-dried and sieved (<1 mm)
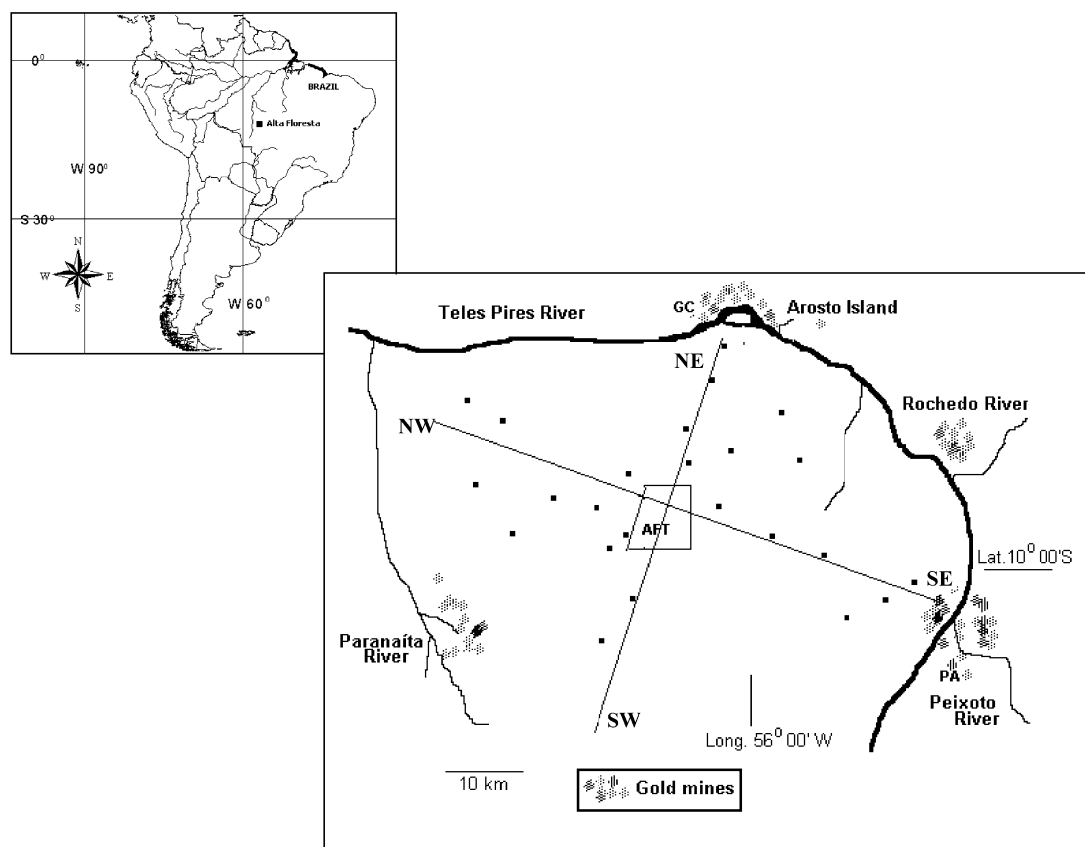

Fig. 2. Map showing the location of the study area and the position of samples (●) in the Alta Floresta region, Mato Grosso State, southern Amazon. AFT: Alta Floresta City.

to remove roots and large grains and/or charcoal particles. Ten g of fresh, soil from each sample were used for pH determination in 1:2.5 water slurry using a glass electrode (Feigl et al., 1995). The remaining samples were split into replicates of each station and oven dried at 50 °C to constant weight. Dried samples were sieved (<1.0 mm) to eliminate roots and other plant debris and rock particles. Sub-samples were combusted at 450 °C for 24 h for the gravimetric estimation of organic matter content. These combusted sub-samples were further digested in *Aqua regia* (1 g sample in 5.0 ml acid) for the determination of total Fe content through conventional flame atomic absorption spectrophotometry.

Mercury was extracted through digestion in 50% *Aqua regia* (1 g of dried soil in 20 ml acid) following Aula et al. (1994) and analyzed by CVAAS in a Bacharaht Model Hg analyzer. Certified reference material (river sediments, U.S. Department of Commerce, National Institute of Standards and Technology) with a Hg concentration of 60 ng g^{-1}, was analyzed using the same procedure. These analyses gave Hg concentrations of 58 ± 3 ng g^{-1}. Standard deviation among sub-samples at the same site were <15% and <10% for Fe and Hg concentrations respectively, and <2% for organic matter content and pH determinations.

3. Results and discussion

3.1. Mercury concentrations in Alta Floresta surface soils

Table 1 shows the mean and standard deviation of four variables measured in Alta Floresta forest and pasture soils. A Mann–Witney U test showed no significant differences (at $P<0.05$) between soils collected at different depths (0–2 vs. 8–10 cm) under the same cover (forest or pasture). The lack of differences between soils depths to 10 cm in soil component concentrations, including trace metals, has been reported previously for other Amazon soils (Herpin et al., 2002). Soil pH was slightly more acidic in subsurface soils than at the surface, but it was not statistically different. The integrated soil column pH from forest and pasture soil samples were statistically different ($P<0.01$), with forest soils being statistically more acidic than pasture soils. Conversion of forest to pasture resulted in a pH increase from 4.76 to 5.71. Since all pasture soils were collected from areas converted not longer than 20 years ago, the increase in pH is expected. Feigl et al. (1995) and Herpin et al. (2002) found that pasture soil pH in Rondônia, Western Amazon, remained elevated, compared to forest soils, for at least 20 years after conversion by forest burning, mostly due to the deposition of large amounts of ash on the soil surface. Ash and charcoal particles were observed in all our pasture samples.

Organic matter, Fe and Hg concentrations were also statistically equal in samples from the two depth intervals. This result allowed the pooling of samples from different depths under the same plant cover for statistical comparison between forest and pasture soils. Organic matter and iron contents exhibited large lateral variation among stations. Organic matter was slightly higher (16.7%) and Fe content slightly lower (2.1%) in forest soils compared to pasture soils (15.4% and 2.47% respectively). Feigl et al. (1995) and Herpin et al. (2002) also reported no significant changes in organic matter and trace element contents, although the sources of carbon to the soil were clearly different. The small Fe increase after conversion may be a result of selective leaching of more mobile elements and a relative increase in the concentration of Fe, a process typical of most tropical latosols (Oliveira et al., 2001).

Mercury concentrations in surface soils varied according to the distance from Hg sources in forest and pasture soils, and exhibited large lateral variability. Mercury concentrations were significantly ($P<0.01$) higher in forest soils (61.9 ± 50.6 ng g^{-1}) than in pasture soils (33.8 ± 13.9 ng g^{-1}). Over 80% of all forest soil samples exhibited Hg concentrations between 50 and 100 ng g^{-1}, with about 70% between 50 and 75 ng g^{-1}, whereas 99% of all pasture samples exhibited Hg concentrations varying from 10 to 50 ng g^{-1}, with 87% being less than 50 ng g^{-1} (Fig. 3). The average concentrations found in Alta Floresta forest soils are in the same range found in most other Amazon areas, such as

Table 1
Physical-chemical characteristics and Hg concentrations in forest and pasture soils (yellow-red latosols, oxisols) from Alta Floresta, MT, southern Amazon

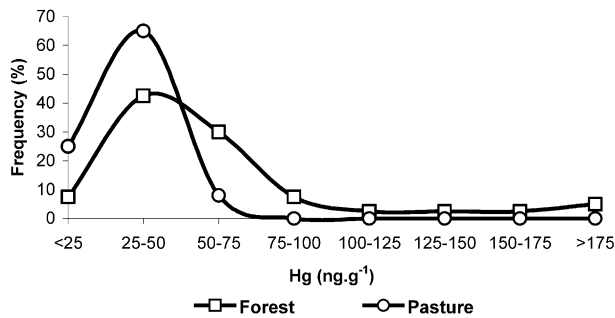| Soil depth	Forest				Pasture			
	pH	OM (%)	Total Fe (%)	Hg (ng.g^{-1})	pH	OM (%)	Total Fe (%)	Hg (ng.g^{-1})
0–2 cm	5.05 ± 0.85	19.1 ± 5.9	2.08 ± 1.2	69.6 ± 58.8	5.77 ± 0.7	18.3 ± 7.9	2.52 ± 1.58	33.6 ± 15.7
$n=31$	(3.6–6.8)	(9.2–29.3)	(0.6–4.8)	(25–248)	(4.3–6.9)	(4.8–25.3)	(0.6–5.9)	(10–74)
8–10 cm	4.46 ± 0.7	15.9 ± 8.8	2.18 ± 1.3	54.2 ± 40.8	5.64 ± 0.6	12.5 ± 6.3	2.42 ± 1.64	33.9 ± 11.7
$n=31$	(3.7–6.5)	(1.4–28.2)	(0.7–5.7)	(15–177)	(4.3–6.5)	(4.0–24.6)	(0.7–5.7)	(21–68)
All depths	4.76 ± 0.78	16.7 ± 7.2	2.1 ± 1.2	61.9 ± 50.6	5.71 ± 0.66	15.4 ± 7.1	2.47 ± 1.61	33.8 ± 13.9
$n=62$	(3.8–6.8)	(1.4–29.3)	(0.6–5.7)	(15–248)	(4.6–6.9)	(4.0–25.3)	(0.6–5.9)	(10–74)

Fig. 3. Frequency distribution of Hg concentrations in pasture and forest soils from Alta Floresta, southern Amazon.

Table 2
Correlation matrix between measured variables in forest and pasture soils of Alta Floresta, MT, southern Amazon

Variable	Forest				Pasture			
	PH	OM	Fe	Hg	pH	OM	Fe	Hg
pH	1.000				1.000			
OM	−0.174	1.000			−0.081	1.000		
Fe	−0.298	−0.149	1.000		−0.032	0.116	1.000	
Hg	−0.360*	−0.080	0.093	1.000	−0.499**	−0.160	0.229	1.000

* $P < 0.05$.
** $P < 0.01$.

the ultisols of the Tapajos River basin, which vary from 44 to 103 ng g^{-1} (Roulet et al., 1998); of the Tocantins River basin with average of 94 ng g^{-1} (Aula et al., 1994); and of the oxisols of the Negro River basin, which vary from 50 to 170 ng g^{-1} (Zeidermann and Forsberg, 1996); and of forest soils of Venezuela, with average Hg concentrations of 103 ng g^{-1} (Shrestha and Quilarte, 1989). Alta Floresta forest soil concentrations, however, were lower than those reported for the Madeira River basin (232–439 ng g^{-1} (Leckler et al., 2000); the yellow oxisols of French Guiana, which vary from 240 to 320 ng g^{-1} (Roulet and Lucotte, 1995); the latosols of Serra do Navio, Amapa, which vary from 100 to 300 ng g^{-1} (Fostier et al., 2000; Oliveira et al., 2000); and the hydromorphic sands and laterites of the Rio Negro basin (average 172 ng g^{-1}, Fadini and Jardim, 2001). Much higher concentrations, however, have been reported for urban soils of Alta Floresta receiving emissions from gold dealer shops, which reach over 1000 ng g^{-1} (Rodrigues and Maddock, 1997), and for soils affected by mining tailings (up to 270 ng g^{-1}) in Central Brazil (Lacerda et al., 1991b). Mercury concentrations in pasture soils in the Amazon, however, are only available for Serra do Navio region in Amapa and showed an average of 63 ± 19 ng g^{-1} for the 0–10 cm layer, also consistently lower than forest soils of the same region (Fostier et al., 2000). Considering the frequency distribution of our samples, however, Hg concentrations in forest and pasture soils of Alta Floresta are in the very lower range of most reported values for the Amazon region.

The two soils types (forest and pasture) are red-yellow latosols with similar composition (Table 2) and equidistant from any Hg source. Therefore, plant cover, i.e. soil use, appears to be the determinant in controlling Hg concentrations. There are many reasons explaining the higher Hg concentrations in forest soils compared to pasture soils. Forested areas better intercept atmospheric Hg than pasture, as shown by higher Hg concentrations in throughfall than in over-canopy rainfall, for example (Fostier et al., 2000). In pasture areas, with higher exposure of the soil surface, higher degassing rates of deposited Hg may occur, resulting in lower Hg

concentrations (Zhang and Lindberg, 1999; Abbott et al., 2003). Preliminary results obtained in Rondônia, western Amazon, showed degassing rates over one order of magnitude higher in pasture than in forest soils (Ebinhaus pers. comm.). Losses to water courses are also larger in pasture areas (Roulet et al., 1999). Forstier et al. (2000) compared erosion rates and Hg distribution in two small basins in Amapa, northern Amazon covered by pasture and forest soils. The Hg flux out of the pasture-dominated basin was over three times larger than out of the forested basin, showing the high capacity of Amazon forest soils to retain Hg and the importance of erosion on pasture areas as a mobilization agent for deposited Hg.

Another important aspect of these pasture soils is that they were formed by burning of the original vegetation which resulted in a nearly complete loss of the Hg present in the former forest soil (Lacerda, 1995). Every 5 years at least, pasture soils in Alta Floresta are burned again, therefore releasing most of the recently deposited Hg (Cordeiro et al., 2002). These burning events, together with stronger degassing, prevent Hg from reaching high concentrations in pasture soils, keeping Hg inputs to the atmosphere higher.

3.2. Lateral distribution of Hg in Alta Floresta surface soils

The influence of the proximity of Hg sources is clearly shown in Fig. 4a–d, for forest and pasture soils, respectively. The Hg concentrations distribution along the two axes followed the predominant wind directions, suggesting that Hg emitted from mining sites to the atmosphere is deposited in the first 40 km from the sites, in particular along the axis following the dominant wind direction, NE–SW (Fig. 4a and c). The influence of the emissions from Alta Floresta urban center seems to be restricted to the first 15 km along the dominant wind direction axis (Fig. 4a and c) and to less than 5 km along the other axis direction, SE–NW (Fig. 4b and d). Other studies have also shown Hg concentrations in soils to be affected by the proximity of mining sites (Lacerda et al., 1991b; Shrestha and Quilarque, 1989).
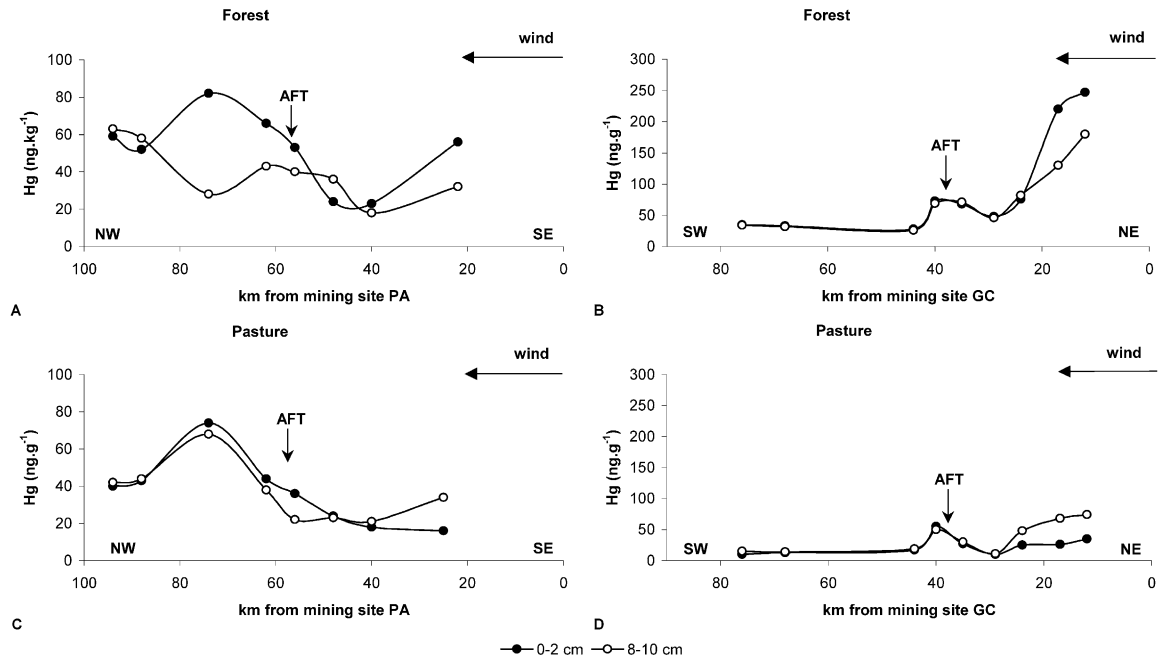
Fig. 4. Mercury concentrations in pasture and forest soils from Alta Floresta, southern Amazon, following different wind directions.

Leady and Gottgens (2001) estimated that from 2 to 8% of the Hg emitted from gold mining sites is deposited locally and the majority can be transported dozens of kilometers from the sites. On the other hand, Hg deposition relatively close to sources has been reported for urban areas containing gold-dealer shops, resulting in the extremely high concentrations found in urban soils (Marins et al., 1991; Hacon et al., 1995; Rodrigues and Maddock, 1997).

It has been demonstrated that particulate Hg dominates the atmospheric emission from gold dealers shops in urban areas. Smelting of gold in these shops involves high temperature pyrolysis using oxidants (Marins and Tonietto, 1995; Marins et al., 2000). This results in rapid Hg deposition over relatively small areas and very high Hg concentrations in urban soils and dust particles. Hacon et al. (1995) estimated that only a small fraction of the Hg emitted by gold dealer shops in Alta Floresta urban area spreads over rural areas. In gold mining sites however, Hg is emitted during the burning of the amalgam at relatively low temperature, resulting in the emission of Hg vapor as the major Hg species, which can disperse to larger areas (Lacerda et al., 1995; Marins et al., 2000). A significant negative correlation, however, was found between soil Hg concentrations and pH (Table 2). Weathered acidic latosols contain large amounts of Fe and Al, which typically adsorb trace metals, including Hg, by surface complexation (Yu, 1997). Studies in Amazon soils suggest that Hg is strongly adsorbed by Al oxides and to a lesser extent by Fe oxides (Roulet et al., 1998; Fadini and Jardim, 2001). It is likely that higher soil pH favors HgII reduction to Hg^0, thereby augmenting

Hg emission to the atmosphere (Zhang and Lindberg, 1999) and resulting in a negative correlation between soil pH and Hg concentrations, as we observe. Also, apart from pH, sunlight strongly accelerates HgII reduction (Zhang and Lindberg, 1999), thus a stronger negative correlation with soil pH would be expected in pasture relative to forest soils, as found in our results. Therefore, the increasing pH typical of Amazon pasture soils, would contribute to enhancing Hg degassing and lower Hg concentrations in pasture relative to forest soils.

It is interesting to note that the effect of land use change on Hg concentrations is also exhibited, although to a much lesser extent, by soil samples collected outside the influence of mining sites (> 40 km). There is no report on the presence of significant geological Hg deposits in the Amazon region. Although traces of Hg are found associated with quartz veins in some regions. Studies on Hg distribution in soil profiles of the Amazon region showed Hg to accumulate in deep, iron-rich horizons (Gonçalves et al., 1998), as a result of downward migration of Hg and adsorption onto Fe and Al oxides. These duricrusts are frequently exposed after forest burning and land preparation for pasture or agriculture. Therefore, the same mechanisms acting upon deposited Hg originated from mining operations can also act on Hg accumulated from natural sources, such as long-term atmospheric deposition and or traces of Hg from geological origin. The mobilization of Hg from deep soil horizons by erosion due to land use changes has been suggested as a partial explanation for the moderately high Hg concentrations found in waters of the Tapajós River Basin (Roulet et al., 1999).

3.3. Mercury burdens in Alta Floresta soils

The cumulative Hg burdens in the studied soils were estimated from surface (0–10 cm) horizons, and from the six deeper cores collected in selected forest sites along the area. As expected, the cumulative (0–10 cm) Hg burden in forest soils was much higher than in pasture soils due to the lower Hg content and higher density observed in pasture soils. Forest soil Hg burdens averaged 8.3 mg m^{-2} for the first 10 cm, and 4.9 mg m^{-2} in pasture soils. Cumulative Hg burdens (0–10 cm) from Alta Floresta forest soils compare well with ultisols (5–13 mg m^{-2}; Roulet et al., 1998) from the Tapajos River Basin and from de Tocantins River Basin (12 mg m^{-2}, Aula et al., 1994); and with hydromorphic oxisols from French Guiana (7.5 mg m^{-2}; Roulet et al., 1998). However, they are much lower than the Hg burdens reported for yellow oxisols from the Tapajos River Basin (9.5–17 mg m^{-2}, Roulet et al., 1998) and from the yellow-red latosols of Serra do Navio, Amapa (18.2 mg m^{-2}, Fostier et al., 2000) and from leached and sandy oxisols from the Negro River basin (18 mg m^{-2}, Fadini and Jardim, 2001).

The origins of the accumulated Hg in Amazon soils is still uncertain. Viera et al. (2001), for example, compared Hg concentrations within modern soils and within paleo-soils from the Alter do Chão Formation, Southeastern Amazon, and found a 100% increase in Hg concentrations in the modern soils. These authors suggested an anthropogenic source as being responsible for this increase. In principal, the amount of Hg in a given soil horizon will be a function of the Hg content of the weathering rock, the soil accumulation/formation rate and the leaching of Hg by percolating waters. Both latter parameters are scarcely reported for the Amazon. The available data on soil horizon ages are quite variable, making difficult the estimate of Hg burdens derived from atmospheric deposition through time. For example, Sanaiotti et al. (2002) presented dating from four forest soil profiles in different regions in the Amazon. They reported ^{14}C dates for charcoal particles collected along the first 1.5 m of soil ranging from 1870 to 5360 years, (average = 3400 years), but no clear constant accumulation rate could be defined. Pessenda et al. (1998b) reported charcoal particle ages collected at about 1 m deep in the soil column at Altamira, northern Amazon, to range between 3700 and 4040 years. These results cannot give precise information on soil accumulation and/or formation rates, since even large particles are capable of downward migration through the soil profile. Notwithstanding this problem, it is reasonable to suppose that our 10 cm soil column could easily accumulate Hg deposition for at least 1000 years, which would account for about 30% of the observed burden, if only the regional atmospheric deposition rates are taken into consideration. However, local atmospheric Hg deposition can be 10 times the regional rates (Cordeiro et al., 2002). Therefore, most of the Hg present in Alta Floresta soils is probably from the local mining site proper, as suggested by the Hg distribution pattern in surface soils shown in this study.

4. Conclusions

The results reported here show a significant impact of small scale gold mining on Hg concentrations and burdens in the Alta Floresta region. Although the importance of Hg atmospheric deposition from other areas in the Amazon cannot be ruled out, it is clear that although gold mining in the region is nearly extinct, the Hg contamination problem is far from solved. Land use change is suggested as a major driver in remobilizing deposited Hg in forest soils, in particular the conversion of forests into pasture. Extrapolating to the entire Amazon region, land use changes will probably keep a large amount of Hg being recycled through the Amazon ecosystems for a very long time, maintaining relatively elevated Hg concentrations in key biological reservoirs, such as carnivorous fish. The implications of such phenomena should be taken into consideration in present and future colonization plans for the region, even when mining activities do not appear to be relevant.

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