

Decrease of soil fertility and release of mercury following deforestation in the Andean Amazon, Napo River Valley, Ecuador

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Abstract

Soil erosion and degradation provoked by deforestation in the Amazon is a global concern, and recent studies propose a link between deforestation, soil erosion and the leaching of naturally occurring mercury (Hg). In the Ecuadorian Amazon, elevated deforestation rates and the proximity of volcanoes could play an important role in soil fertility and soil Hg levels. The goal of this study is to evaluate the impacts of deforestation on Andisol and Inceptisol fertility and Hg levels in the Napo River Valley, Ecuador. Results show a significant decrease in surface soil organic matter (–15% to –70% of C and N) and exchangeable cations (–25% to –60%) in deforested plots. Hg concentrations at the surface (0–5cm), higher in Andisols (225 ng/g average) than in Inceptisols (95 ng/g average), show a decrease of up to 60% following deforestation. Soil erosion exposes the mineral horizon, a layer with a higher Hg burden, to the elements thus provoking and accelerating Hg leaching. These results suggest that deforestation and the associated Hg leaching could contribute to the fish Hg contamination measured in the Napo River watershed.

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1. Introduction

High deforestation rates in the Amazon are the source of scientific concerns. Being the host of two of the three main Amazonian deforestation fronts identified by Myers (1993), the Andean Amazon, shared

between Columbia, Ecuador, Peru and Bolivia, has undergone a recent upsurge of environmental, socio-economical and political changes. Land-use changes are particularly dynamic in the Ecuadorian Amazon, a biodiversity “hotspot” (Myers et al., 2000) that was opened to active colonization in the 1970's through the construction of roads used for oil exploitation by foreign petroleum companies (Rudel and Horowitz, 1993; Murphy et al., 1997; Marquette, 1998; Sierra, 2000). Allowing farmers to establish themselves on

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roadsides, pipeline construction lead to one of the most active deforestation fronts in South America, a region now called the Napo deforestation front because it is mainly concentrated in the Napo River Valley of the Ecuadorian Amazon (Sierra, 2000). According to Sierra (2000), more than 85% of the land cleared in this region is dedicated to pasture.

The biotic and non-biotic impacts of deforestation in the Amazon are diverse. Some of the most critical changes induced by land clearing are the drastic loss of fertility and compaction of soils which follow the increase of soil erosion and the alteration of the primary soil nutrient bank, the thin top layer composed of organic matter (eg. Chauvel et al., 1991; Grimaldi et al., 1993; Tiesen et al., 1994; Farella et al., 2001). Recent studies have suggested that deforestation leads to the leaching of a neurotoxic heavy metal contained in the Amazonian soils: mercury (Hg) (Roulet et al., 1998a,b, 1999, 2000; Fostier et al., 2000; Farella et al., 2001). It is well known that Amazonian soils are an important Hg reservoir due to their long history of accumulation (Roulet and Lucotte, 1995; Roulet et al., 1998b; Richard et al., 2000; Lechler et al., 2000; Fostier et al., 2000; De Oliveira et al., 2001; Fadini and Jardim, 2001; Brabo et al., 2003). Research conducted by Roulet et al. (1998b, 1999, 2000) and later by Fostier et al. (2000) has evaluated the impacts of erosion on different soil types including changes in Hg levels. Their results indicate that soil erosion, increased by deforestation, acts as a source of Hg to aquatic ecosystems, thus adding an additional parameter in the evaluation of fish contamination and Hg dynamics, before studied only in relation to gold mining activities as a punctual Hg source (Lacerda, 1997; Malm, 1998) or Hg volatilization from “slash and burn” practices as a diffuse source (Veiga et al., 1994; Roulet et al., 1999).

In the Brazilian Amazon, many studies have found fish consumed by riparian communities to be contaminated in Hg (Akagi et al., 1995; Malm et al., 1995, 1997; Lebel et al., 1997; Souza Lima et al., 2000; Sampaio da Silva et al., 2005), while other studies have observed subtle health effects in these communities due to Hg exposure (Lebel et al., 1996; Brabo et al., 2000; Dolbec et al., 2000). Increasingly, widespread deforestation is an important parameter to consider when evaluating the health risks associated with the consumption of fish containing Hg. Even though two of the three Amazonian deforestation fronts are outside of Brazil, very little is known about the Hg dynamics in Amazonian countries other than Brazil (Wasserman et al., 2003).

The Hg dynamic in the Andean Amazon is greatly influenced by the Andean *cordillera* (Maurice-Bourgoin et al., 2003). This region is considered to be one of the most active “mercury belts” on Earth due to its constant volcanic and tectonic activity, releasing more than 29 tonnes of Hg per year (Nriagu and Becker, 2003). These emissions can travel long distances or deposit nearby through volcanic ash and ejecta (Gustin et al., 2000; Tomiyasu et al., 2003; Hernandez et al., 2004). Volcanic ash soils are liable to contain significant Hg levels due to their provenance and their high cation absorption capacity (Wada, 1985; Shoji et al., 1993), although few studies have attempted to measure Hg levels in volcanic soils (Tomiyasu et al., 2003; Hernandez et al., 2004) and no information exists on the Andes specifically. In the Ecuadorian Amazon, where a parallel study has shown relatively high Hg levels in certain fish species (Webb et al., 2004), elevated erosion levels provoked by intense precipitations (up to 8000 mm/y; Cañadas Cruz, 1983), accentuated relief and high deforestation rates (De Noni et al., 1986) could lead to the leaching of soil Hg and represent an important Hg source to the aquatic ecosystems. Webb et al. (2004) also showed a relationship between fish consumption habits and Hg levels in the hair of three riparian communities.

The present study evaluates the impacts of deforestation on soil fertility and Hg levels through a comparison of pristine (primary forest) and cleared land (pasture) in the Napo River Valley, Ecuador. The goal of our research is to determine whether deforestation in this highly colonized area represents a source of Hg to the aquatic ecosystems and if Andisols react more to land clearing than Inceptisols.

2. Methods

2.1. Study area

This study was carried out in the Napo River watershed, an area comprised of a wide variety of soil types and climatic conditions, extending from the top of the Cotopaxi volcano to the beginning of the Peruvian Amazon River. Three distinct regions (Andes, foothills and basin later referred as “Andes”, “FH” and “B”) were selected for this study, according to an East–West gradient along the river, as shown in Fig. 1. The Andes sampling site, located at an altitude of 1200 m, is characterized by accentuated relief, dense cloud forest, very high annual precipitations (5000 to 8000 mm/y) and agricultural land concen-

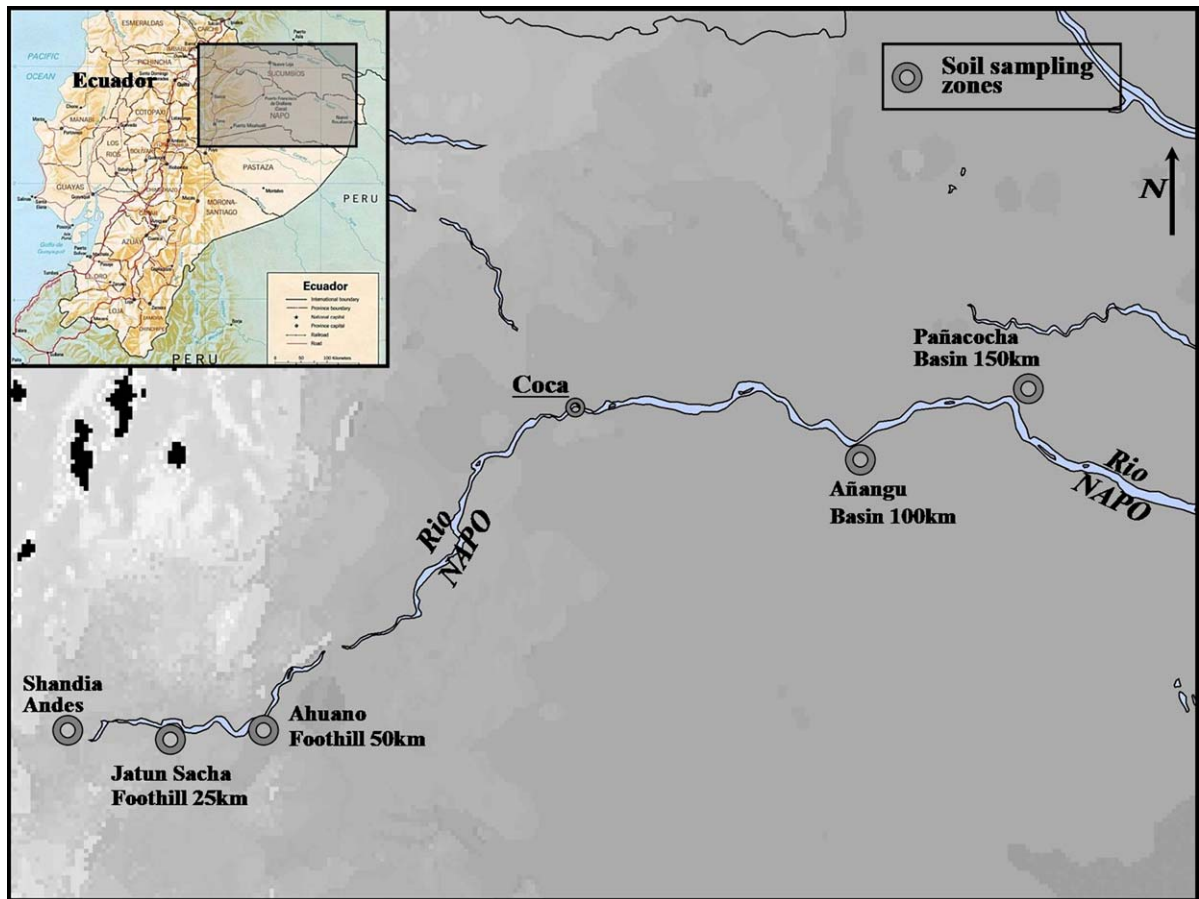


Fig. 1. Map of study area, Napo River Valley, Ecuadorian Amazon, showing the five sampling zones.

trated on plateaus (Cañadas Cruz, 1983). The foothill sampling sites, represented by FH25km and FH50km according to their distance with the Andes, correspond to the transition zone between the mountains and the basin. This region receives a little less precipitation (around 5000 mm/y) than in the Andes (Cañadas Cruz, 1983), has variable relief, from steep hills to plateaus, dense tropical rain forest and extensive areas dedicated to pasture and agriculture. The basin sampling sites, represented by B100 km and B150 km and characterized by plateaus and typical Amazonian rain forest, receives around 3500 mm/y of precipitation (Cañadas Cruz, 1983) and is intensively colonized on riverbanks. No artisanal gold mining takes place in the study area.

2.2. Sampling

Soil samples were collected during two sampling campaigns, January 2002 and June 2002. The five sampling zones were selected according to the type of

land use (primary forest vs. pasture) and their proximity to the river, ensuring that the pasture and the primary forest were one beside the other to prevent the chances of sampling different soil types (Table 1). Pastures were predominantly covered by “pasto elephante” (*Pennisetum purpureum* Schumach), “dallies” (*Paspalum dilatatum* Poir) or “gramalote” (*Panicum purpurascens* Raddi), three popular species used in this area (Rudel and Horowitz, 1993; FAO-AFRIS, 2004). The age of the pastures, varying from 4 to 30 years old, were determined through personal communication with land owners; however, it was impossible to precisely identify the age of on-going cultivation and the history of shifting cultivation.

On each forest and pasture sampling site, three transects (5 m apart) made of three points (5, 50 and 100 m from the river) dug to three depths (0–5, 20–25, 45–50 cm) were sampled, for a total of 27 samples per site and 54 samples per zone. The soil samples were collected with a fixed volume tubular corer (100 cm³), transferred into Ziploc bags, air dried in the shade and

Table 1
Regional characteristics of sampling sites in the Napo River Valley, Ecuador

Sampling zone (distance from the Andes)	District	Altitude (m)	Precipitation (mm/year)	Slope at the site (°)		Characteristics	
				Forest	Pasture	Forest	Pasture
Andes	Shandia	1200	5000–8000	<5	<5	Cloud forest black moist spongy soil 5 cm thick humus	“Gramotole” aprox. 4 years black moist spongy soil flat plateau
Foothill 25 km	Jatun Sacha	400	6000	<5	<2	Flooding zone–dense rainforest Hydromorphic soil Lithic contact less than 1 m	“Dalis” aprox. 20 years flooding zone–pentanal fibre at the surface
Foothill 50 km	Ahuano	400	6000	25	25	Steep slope no OM accumulation perturbation–light brown soil	“Pasto elefante” aprox. 10 years steep slope landslide in some places
Basin 100 km	Anangu	250	3500	20	20	Hills, heterogenous relief slightly retreated from the river brown soil	“Dalis” aprox. 30 years abandoned, steep very compact soil
Basin 150 km	Panacocha	200	3500	10	15	Close to flooding zone close to perturbation red brown soil	“Dalis” aprox. 15 years very compact soil fruit trees on bottom slope

then brought back to our Montreal laboratory for analysis.

2.3. Lab analyses

All the soil samples were dried in a stove at 40 °C. Once dry, the samples were ground in a mortar and sifted using a 2 mm sieve. Total density was calculated before grinding. Levels of total carbon (C) and nitrogen (N) were determined by elementary detection (Carlo-Erba NA-1500 analyzer), exchangeable cations (Al, Ca, Mg, Mn, K, Fe), later referred as the ECEC were extracted with the BaCl₂ 0,1M method (Hendershot et al., 1993) and then analyzed with atomic absorption. Inorganic nitrogen (NH₄ and NO₃) was extracted with a 2M KCl solution and analyzed with flow injection analysis Tecator (FIAstar 5020 analyser). Percentage of nitrate was calculated, in order to measure its relative importance in the nitrogen fraction, using the following equation: % NO₃ = (NO₃ / (NO₃ + NH₄)) * 100.

Total Hg levels were measured with the Cold Vapour Atomic Fluorescence (CVAF) technique according to the protocol of Pichet et al. (1999). Briefly, 250 mg of soil was digested in a 10:1 nitric and hydrochloric acid mixture, heated at 120 °C and then injected in a spectrophotometer. Hg burdens were first calculated for each centimetre of soil with the average Hg concentration and density for each depth (0–5, 20–25, 45–50 cm). The sum of the three intervals (0–5, 5–25 and 25–50 cm) was made to evaluate the Hg burdens for the total 50 cm.

2.4. Pedological classification

Most of the pedological studies conducted in the Ecuadorian Amazon have been carried out by the ORSTOM team (now IRD-Institut de Recherche et de Développement) in the 1980s. This work, in conjunction with the Ecuadorian government (Instituto Geografico Militar IGM), made possible the creation of several soil maps of the region (MAG-PRONAREG and ORSTOM, 1983; De Noni et al., 1986; Sourdat, 1986). Each study concluded that the high soil diversity in this area made classical taxonomic classification a daunting task. Because our sampling was relatively restricted on the field, we use these studies as a basis for the classification of the soils sampled in our study.

2.5. Statistical analyses

The influence of toposequence (top, middle and bottom of slope), of depth (0–5, 20–25, 45–50 cm) and of land use type (forest or pasture) on soil fertility parameters (C, N, ECEC, Sum of bases, NH₄ and NO₃) and Hg levels were analyzed through ANOVA statistical tests. The “slope” and “land use” effects were also analyzed with multiple comparisons (Tukey test). The “depth” effect was analyzed through an ANOVA only for the Hg levels. Statistical significance was set at 95% and the calculations were conducted with the SAS 8.0 and SPSS 11.0 software.

3. Results

3.1. Soils classification

The chemical and physical properties of the sampled soils (see Mainville (2004) for a complete description), in accordance with the literature (Sourdat, 1986; Soil Survey Staff, 1994), show distinct differences between the Andean region (Andisols) and the two lower laying regions of the study (Inceptisols). The soil parameters indicate that the soils sampled in the Andean region correspond to *hydrudands* (before called *hydrandepts*), which are permanently hydrated Andisols with high OM content and Al toxicity. The FH25km soils are classified as *aquic eutropepts* due to their high base saturation levels and their “*aquic*” conditions (Sourdat, 1986; Soil Survey Staff, 1994). The steep slope and the apparent perturbations (isolated landslides) observed at the FH50km sites compel us to classify these soils as perturbed Inceptisols with characteristics corresponding to the *tropepts* suborder (Sourdat, 1986; Soil Survey Staff, 1994). Finally, the two basin sites’ soil characteristics correspond to the brown *halloysitic-andic* soils (brown A) described by Sourdat (1986). These *ferrallitic* and *eutric* soils, found mainly in the Napo River watershed, have a partially volcanic origin, which plays a predominant role on their physical and chemical characteristics.

3.2. Statistical variance

No significant difference between points on the slope for each depth ($p > 0,05$) were found for Hg, C, N or ECEC which allows for the fusion of the three points into one average for each depth. Differences between the three transects (replicates), were not significant either, although they were greater in the pasture. The absence of statistical difference between the transects made possible the fusion of all the results into one average value for each depth ($n=9$).

3.3. Influence of deforestation on surface soil fertility

Because it is the main interface with vegetation, only the surface level results will be considered in this section on soil fertility. As shown in Fig. 2, the ECEC levels are, for each of the five zones, significantly lower ($p < 0,05$) in the pasture than in the forest. This tendency is also observable for the sum of bases, except for the FH50km zone for which the variance is high and no significant difference was noted. The pastures show a significant decrease ($p < 0,05$) in C as

compared to the forest in all of the zones except FH25 km, while N values are lower in pastures of all regions except FH25km and the Andes.

There is no significant difference between forest and pasture NH_4 levels in any of the zones; however, the NO_3 relative percentage values show a consistent effect of land clearing, with the exception of the FH50km zone that possesses very low NO_3 levels under both land-use types. When observing the other zones, the relative NO_3 under forest cover dominates the NH_4 levels but drops drastically under pasture tenure. The mineral nitrogen fraction, and particularly the NO_3 levels, seems more affected by land clearing than the total nitrogen (%N), thus suggesting that it could act as a better soil degradation indicator.

3.4. Influence of deforestation on Hg levels

Hg levels in forests and pastures at the three depths are shown in Fig. 3. There is a significant reduction ($p < 0,05$) of Hg in the pastures in all zones at the surface level, in two of the zones at 20–25 cm and in only one zone at 45–50 cm. Hg burdens for all three depths (0–5, 5–25, 25–50 cm) and for the combined 50 cm are shown in Table 2. At the surface level and when considering the total 50 cm, each zone exhibits a significant decrease ($p < 0,05$) of Hg burden under pasture. This attenuation is also perceived between 5 and 25 cm, except in zone FH25 km. Finally, Hg burdens between 25 and 50 cm are less affected by land clearing, where only two zones show a significant decrease ($p < 0,05$) between forest and pasture. The B100 km site shows the largest decrease in Hg burden between 5 and 25 cm.

4. Discussion

4.1. Impacts of deforestation on soil fertility

The abrupt transition from forest to pasture provokes a net surface loss of exchangeable cations and organic matter (here shown by C and N) in most zones. Table 3 summarizes these losses in percentages. Because of high precipitation and humidity, most of the land clearing taking place in the Ecuadorian Amazon is based on the “slash and mulch” technique, as opposed to the widespread “slash and burn” process used in central Amazon (Rudel and Horowitz, 1993). Burning the forest increases soil fertility through deposition of ash, but it is now well known that this increase lasts only for a short period and that soil erosion and nutrient leaching leads to an impoverishment of Amazonian soils (Desjardins et al., 1994; Williams et al., 1997;

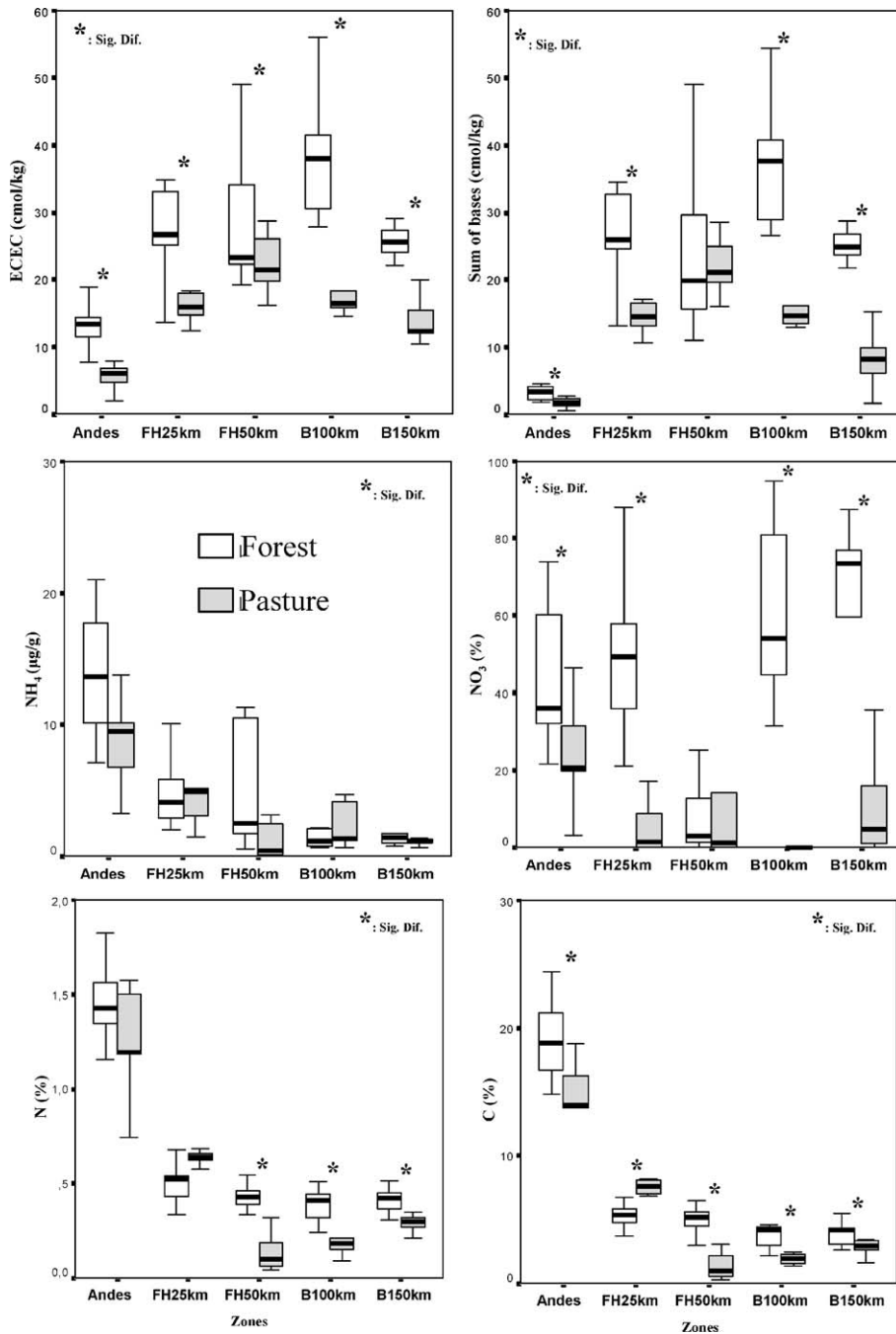


Fig. 2. Influence of deforestation on surface soil fertility ($n=9$).

Sommer et al., 2004). As shown by Sommer et al. (2004), “slash and mulch” agriculture is a more sustainable land clearing technique because it allows for a better recycling of nutrients. However, the net loss of nutrients in the pasture observed in our study shows that the soil system in the Ecuadorian Amazon is vulnerable to soil depredation after deforestation.

The differences between soil fertility in forests and pastures can be primarily explained by a severe decrease of organic matter input to the litter once the forest is extracted from the system. It is also important to highlight the intensity of rainfall in this Andean Amazon region. Precipitation two to three times higher than in the central Amazonian basin undeniably plays a

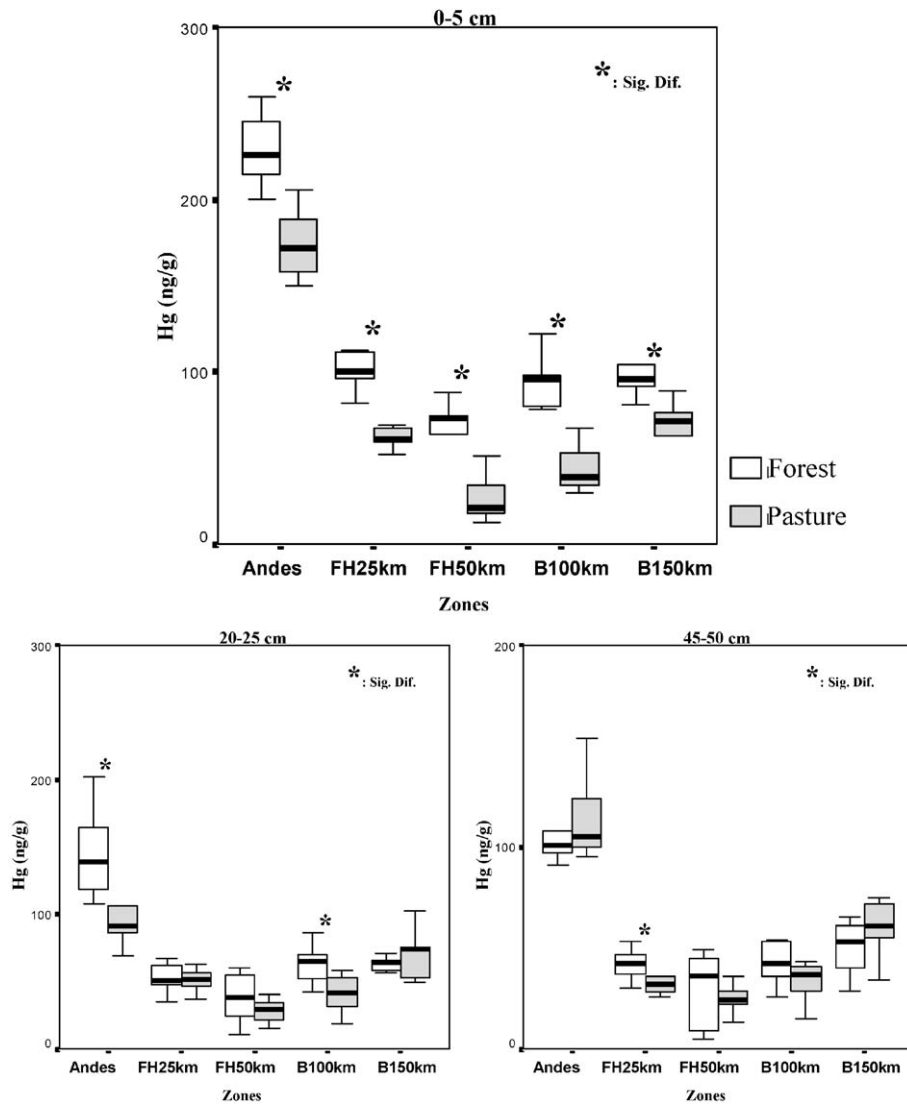


Fig. 3. Influence of deforestation on soil Hg concentration at three depths ($n=9$).

crucial role in fertility loss through nutrient leaching. This phenomenon is well illustrated by the C and N decrease of up to 65%, and the sum of bases and ECEC losses of almost 70% in some zones (Table 3). It is interesting to observe an increase from forest to pasture of C and N in the FH25km zone, where soils are

hydromorphic and thus have a very low decomposition rate and allow for organic matter accumulation.

The Andisols show a smaller loss of organic matter (represented by C and N) in comparison to the four other zones. This difference can be explained by the youth of the pasture sampled in this study and by the

Table 2
Average soil Hg burden (QHg) calculated for the first 50 cm

QHg (mg/m ²)	Depth (cm)	Andes		Foothill 25 km		Foothill 50 km		Basin 100 km		Basin 150 km	
		Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture	Forest	Pasture
	0–5	2,9	2,4	2,5	1,2	2,1	1,2	3,4	2,1	4,1	4,4
	5–25	11,7	9,5	8,9	9,6	7,2	6,0	13,3	9,9	16,0	15,8
	25–50	11,2	11,9	9,1	7,8	7,6	8,7	12,0	12,1	17,2	16,5
	0–50	25,7	23,8	20,5	18,6	17,0	15,9	28,7	24,1	37,3	35,7

Table 3
Percentage difference between pastures and forests soil characteristics

		Andes	FH25km	FH50km	B100km	B150km
Exchangeable cations	ECEC	-58	-33	-26	-50	-49
	K	49	18	-50	-38	-32
	Ca	-48	-38	-3	-57	-73
	Mg	-45	-34	-40	-46	-56
	Sum	-47	-36	-15	-55	-69
OM	N	-16	32	-59	-55	-33
	C	-25	60	-68	-50	-28
Hg surface	[Hg]	-25	-41	-60	-53	-32
	QHg 0–5 cm	-18	-52	-45	-38	-17
	QHg 0–25 cm	-18	-5	-24	-28	-5

very low inclination at the sampling site. Even if the total loss after clearing is smaller in volcanic ash soils, the influence of this loss on soil fertility is important. A 25% decrease of OM content can have a significant impact on soil fertility because OM in Andisols plays a central role in exchangeable cations retention (Oades et al., 1989; Shoji et al., 1993; Davidson et al., 1999). A study conducted by Davidson et al. (1999) showed that a net OM loss of 25% in Ecuadorian Amazonian degraded Andisols resulted in a 77% loss of ECEC, thus incurring a reduction of cultivation productivity. In our study, high C-ECEC correlation ratios indicate that this same relationship is present in the Andisols sampled under forest and pasture ($R^2=0,972$ for forest, $R^2=0,975$ for pasture; results not shown). It is also important to mention that Andisols are known for their vulnerability to deforestation and erosion due to their irreversible structural loss after desiccation and compacting, thus forming almost sterile soils called “cangahua” (Zebrowski et al., 1997). Despite the fact that this is a widespread phenomenon in mountainous agriculture, “cangahua” was not observed on our sampling site.

Transition from forest to pasture did not affect NH_4 levels in each of the zones studied, which does not correspond to our original hypothesis. Our results suggest that the bacteria flora responsible for ammonification is little affected by “slash and mulch” clearing or that it recuperates quickly after perturbation. However, nitrate levels seem highly impacted by land clearing, drastic losses being observed in every zone except for the perturbed Inceptisols (FH50km). Exposition to rainfall and changes in physical characteristics after clearing (soil temperature, humidex) seem to influence greatly the soil’s nitrification pro-

cess and to accentuate nitrate leaching, thus influencing nitrogen availability and plant productivity. These results correspond to other studies conducted in the same region on volcanic soils (Davidson et al., 1998). The particularity of the FH50km zone can be attributed to the very low litter accumulation, the steep slope and the high erosion levels found on the pasture site.

4.2. Impacts of deforestation on Hg concentrations

Land clearing and pasture establishment seem to affect surface soil Hg levels as much as their fertility, where a net loss of up to 60% can be observed in certain zones (Table 3). Mainville (2004) shows that under forest, each zone presents very strong correlations between soil Hg and OM content (R^2 from 0,85 to 0,93). The net decrease of C and N observed in the pasture seems to imply that Hg migrates with the OM it is associated with. Because land clearing in the study area is not driven by “slash and burn” agriculture, a technique allowing surface soil Hg volatilization (Roulet et al., 1999), Hg migration outside the soil system can be achieved in two ways: erosion and subsequent leaching, or volatilization due to an increase of surface soil temperature (Fostier et al., 2000). Even if a combination of the two factors is probably at work, Hg migration is certainly mostly related to soil erosion because of the particularly rainy conditions in the region. This dominance cannot be demonstrated through this study, but severe surface cation losses and higher Hg decreases on more sloped sampling sites give us a good indication of the role of erosion in the system studied here.

The effects of deforestation on subsurface Hg concentrations are less perceptible. As proposed by Mainville (2004), the soils of the Napo River Valley are very young and have a limited pedogenesis, the podzolization process being almost absent. Soil Hg in forests is located mainly at the surface level because it is associated with the OM, which itself slows down the vertical migration of Hg. Little differences between forest and pasture Hg concentration at 20–25 and 45–50 cm demonstrate that environmental conditions have an influence primarily at the surface. The selective erosion resulting in a migration of small particles and associated Hg to deeper levels proposed by Roulet et al. (1998b), was not observed. These observations correlate with the rest of our results indicating that there is no “slope effect”, the Hg concentrations being quite the same either on the top, middle or bottom of the slope.

4.3. Impacts of deforestation on Hg burdens

The amount of Hg exported from the edaphic system can be evaluated by comparing Hg burdens in forested and deforested sites. This approach allows us to determine the role of the soils as a source of Hg. At the surface, the decrease of Hg burden in pasture is from 18 to 50% (Table 3), which represents, for the entire region, an average of 0,95 mg/m² of Hg exiting the surface soils (Table 2). This value is quite low due to the low topsoil density but the calculation does not include Hg migration associated with litter loss. This parameter was not part of the present study. Roulet et al. (1998b) observed a net loss of approximately 5 cm of topsoil after deforestation, and, considering that all the litter and the organic horizon are removed from the system as well, they calculate an export of Hg from 0,25 to 4,6 mg/m². Even though we observe a significant loss of OM at the surface, the amount of Hg exiting the surface soil system seems lower than what was observed in the Brazilian Amazon.

Nonetheless, superficial erosion has deleterious effects. The subtraction of the top organic horizon, as observed in our study, implies an exposition of the mineral horizons to the elements. These compartments of the soil have a higher Hg burden, from three to five times more than at the surface, due to their higher density (Table 2). Subsequent conversion to pasture provokes a cascade of Hg liberation from the soil system, liberating a small amount from the top layers and then exposing mineral horizons with higher Hg burdens. Even though we observe a lesser proportion of Hg exiting the system between 5 to 25 cm (~10%) than at the surface (~34%), the absolute amount of Hg exiting is higher at depth (1,26 mg/m²) than at the surface (0,95 mg/m²). When evaluating the differences between Hg burdens in forest and pasture at 25 to 50 cm, there is no significant decrease. This observation shows, once again, that selective erosion and in depth leaching is very limited in this region as opposed to what is observed in the Tapajos River watershed (Roulet et al., 1998b).

When evaluating the Hg liberation cascade in only volcanic soils, surface decrease is relatively low (0,5 mg/m² (-18%)). High OM levels in the particular pasture studied may be tempering deforestation impacts by fixing and retaining the Hg. In comparison with the surface, the same proportion of Hg (-18%) is exported from the system at 5 to 25 cm, however this decrease implies a release of four times more Hg (2,15 mg/m²) from the soil. When comparing all the zones together, it is the B100km that shows the most drastic liberation of

Hg (-3,4 mg/m² at 5–25 cm), which is probably due to the old age of the pasture, the abrupt slope and the state of environmental degradation (see Table 1). Because the pasture in the Andes is the youngest of all and its slope is almost inexistent, and because, despite of this, there is a significant release of Hg from these soils, the Andisols sampled seem to be the most sensitive to land clearing. Hence, the impacts of deforestation and pasture establishment seem to be modulated by the duration of soil exposure, the slope and the type of soil under which the pasture was established.

However, the soils studied in this region seem to release less Hg after land clearing than what is observed on the Tapajos (Roulet et al., 1998b) and the Pedra Preta basins (Fostier et al., 2000). As explained by Mainville (2004), the Hg burdens measured are lower than the ones in the central Amazon because the soils sampled here are younger and have not been accumulating Hg for millions of years as soils in Brazil have. Our calculations show that an average of 2,2 mg/m² of Hg exits the first 25 cm of soil after land clearing, which represents a loss of 16% (for the entire region). Roulet et al. (1998b) observe for the first 20 cm of cultivated soils a release from 4 to 10 mg/m² of Hg (a loss of approximately 20% to 50%). Fostier et al. (2000) measured differences between forested and deforested plots of a magnitude of 29 mg/m² for the first 10 cm, a loss of almost 80%. Therefore, even though harsh precipitation and erosion conditions exist in the Ecuadorian Amazon, the soils studied liberate less Hg after clearing than the soils in the Brazilian Amazon. This could be attributed to the low Hg burdens of the studied soils and the primarily superficial influence that deforestation has on these soils.

5. Conclusion

The study results show that, once deforested, the soils of the Napo River Valley are susceptible to significant and deleterious changes. Loss of exchangeable cations and nitrates is a predominant change that reduces soil fertility and limits cultivation productivity after clearing. Surface soil erosion is the main mechanism under which these changes appear. Land clearing also provokes considerable loss of soil Hg and instigates Hg liberation towards aquatic ecosystems. Actual colonization and deforestation rates in the Ecuadorian Amazon, coupled with more than 2 million hectares of already cleared land, catalyzes Hg liberation from the soils and leads one to believe that deforestation contributes to the contamination of certain piscivorous fish species as measured by Webb et al. (2004). The

amount of Hg exported from the Ecuadorian Amazonian soils seems to be less than that measured in the Brazilian Amazon, which can be explained by the lower Hg burdens of the Ecuadorian soils and the largely superficial impact of deforestation in this Andean region. The use of Hg as a soil perturbation index and the threat it poses as an aquatic contaminant can serve to promote more sustainable agricultural practices that reduce erosion and thus preserve the health of riparian communities.

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