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Deforestation and forest regeneration following small-scale gold mining in the Amazon: the case of Suriname

GARRY D. PETERSON[1]* AND MARIEKE HEEMSKERK[2]

[1]Center for Limnology, University of Wisconsin, Madison WI 53706, USA and [2]Department of Rural Sociology, University of Wisconsin, Madison WI 53706, USA

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Summary

Despite scientific concern about Amazon deforestation and the impacts of the Amazon gold rush, few researchers have assessed the long-term impacts of small-scale gold mining on forest cover. This study estimates deforestation from gold mining and analyses the regeneration of abandoned mining areas in the Suriname Amazon. Fieldwork in December 1998 included observations and ecological measurements, as well as qualitative interviews with local miners about mining history and technology. Vegetation cover of abandoned mining sites of different ages was compared with that in old-growth forest. By present estimates, gold miners clear 48–96 km^2 of old-growth forest in Suriname annually. Based on different assumptions about changes in technology and the amount of mining that takes place on previously mined sites, cumulative deforestation is expected to reach 750–2280 km^2 by 2010. Furthermore, the analysis of abandoned mining sites suggests that forest recovery following mining is slow and qualitatively inferior compared to regeneration following other land uses. Unlike areas in nearby old-growth forest, large parts of mined areas remain bare ground, grass, and standing water. The area deforested by mining may seem relatively small, but given the slow forest recovery and the concentration of mining in selected areas, small-scale gold mining is expected to reduce local forest cover and ecosystem services in regions where mining takes place.

Keywords: small-scale gold mining, Amazon, Suriname, deforestation, regeneration, land use/land cover change

Introduction

Environmental degradation caused by small-scale gold miners is threatening the Amazon rain forest and the livelihoods of the people who depend on forest resources (Healy 1996; MacMillan 1996; Veiga 1997*a*). Researchers have documented many impacts of small-scale gold mining, including violent conflict, the spread of malaria and sexually transmitted diseases, and mercury pollution of people and aquatic resources (Akagi *et al*. 1995; Veiga *et al*. 1995; Bezerra *et al*. 1996; MacMillan 1995; Cleary 1990; Faas *et al*. 1999). However, to our knowledge no one has analysed how much forest is cleared by small-scale gold miners, nor assessed the quality and pace of forest recovery following mining. The limited attention paid to mining-induced deforestation is surprising given the scientific and public concern about conservation of the Amazon rain forest and about the impacts of small-scale gold mining.

The objective of this study is to analyse the relative impact of small-scale gold mining on forest cover in the Suriname portion of the Amazon rainforest. Our principal questions are: (1) how much old-growth forest do small-scale gold miners remove, and (2) what is the pace and quality of forest regeneration on abandoned mining sites over time? We address these questions in three steps. First, based on our measurement and expert estimates of relevant variables, we estimate the area cleared by small-scale gold miners. Second, we use ecological measurements to estimate the pace and quality of forest regeneration at abandoned gold mining sites. Third, by comparing forest regeneration following mining with regeneration following other land-uses, we assess the relative impact of the present small-scale gold mining boom on the Amazon rain forest.

Study site

Suriname, formerly Dutch Guyana, is located north of Brazil, between Guyana and French Guiana. The tropical rain forests that cover 80% of Suriname have been classified by the World Resources Institute (1999) as ‘frontier forests’, meaning they are large, relatively intact forest ecosystems that are dominated by indigenous vegetation and animal species. The small Suriname population of 409 000 (ABS 1997) lives almost entirely in or near the capital city of Paramaribo. The forest is occupied by tribal peoples, whose combined populations are estimated to be between 55 000 and 65 000 (Kambel & MacKay 1999). Due to its informal and quasi-legal character, statistics concerning the gold mining sector in Suriname are highly speculative. Estimates of the number of people involved in gold mining range from 10 000 to 20 000, and the most reliable estimates of annual gold production range from 10 to 12 tonnes (Healy 1996; Veiga 1997*b*; De Kom *et al*. 1998).

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* Correspondence: Dr G.D. Peterson Tel: +1 608 2623088 e-mail: gdpeterson@facstaff.wisc.edu

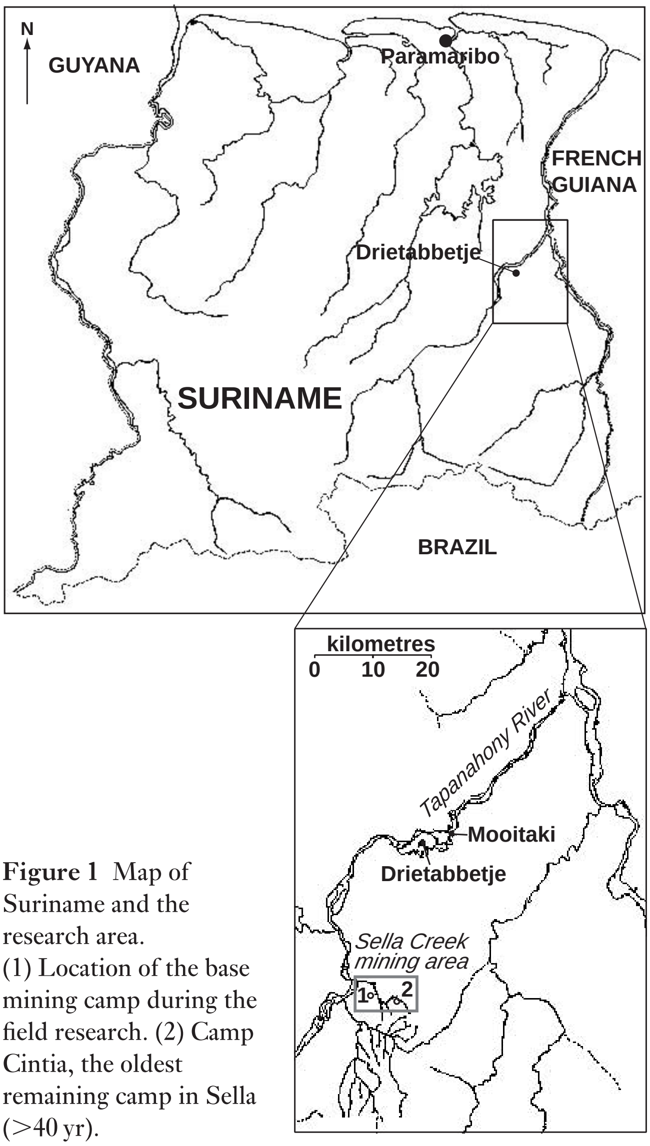

Figure 1 Map of Suriname and the research area. (1) Location of the base mining camp during the field research. (2) Camp Cintia, the oldest remaining camp in Sella (>40 yr).

In December 1998, we conducted research at the Sella Creek gold mining area in Eastern Suriname. Sella Creek is a small tributary of the Tapanahony River (Fig. 1). The mining area does not have an airstrip and is only accessible by boat. We worked at this site because Heemskerk's (2000*a*) anthropological research had established familiarity with the area and good relationships with the local miners. These miners provided us with food, shelter, and assistance. We estimated that Sella Creek has between 60 and 70 gold mining camps that house a shifting population of about 700 people. Our data suggest that the total gold production of Sella Creek is between 1.5 and 2.5 tonnes yr^{-1}, which accounts for 12 ± 5 % of Suriname's total gold production (De Kom *et al.* 1998).

Gold miners at Sella Creek primarily mine land-based secondary gold deposits that are sometimes near forest creeks and rivers. Hydraulic mining machines with six-inch (15-cm) pumps are currently the predominant mining method.

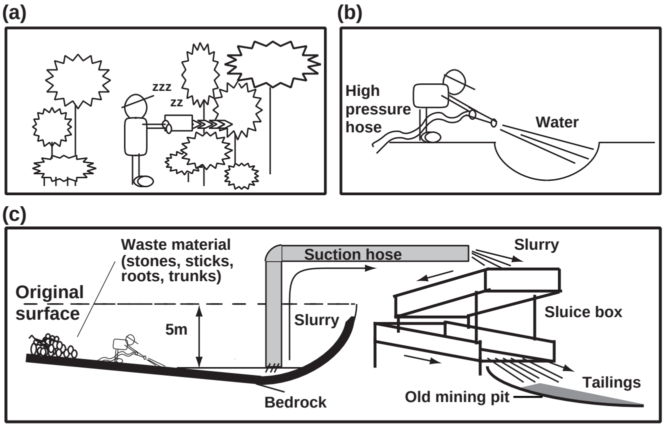

Figure 2 Illustration of the small-scale gold mining process. (*a*) First the forest is cleared. All easily cut trees are cut and then burned. Trees that are difficult to remove remain standing. The cleared area is about 80 x 80 m. (*b*) High pressure water is used to remove the topsoil, and later the gold-bearing layer of sand and clay. This work is done by about five people. (*c*) The gold bearing slurry is pumped into a sluice box, which collects gold particles, while mine tailings flow into either an abandoned mining pit or adjacent forest. As a mining pit is cut, material that could clog the suction hose, such as rocks, roots, and woody debris, is removed from the mining pit and placed beside it.

Hydraulic mining methods are explained in Figure 2. Miners elsewhere in Suriname also use bulldozers and excavators. The difficult access to the Sella Creek mining area has prevented the transport and application of heavier machinery in this area. As a result the extrapolation of our estimates to Suriname will be conservative.

Methods

We used a combination of social science and ecological methods to analyse deforestation in Suriname. First, we used estimates of size and history of Suriname's gold mining industry at large in combination with detailed anthropological knowledge of gold mining to estimate the amount of deforestation produced by gold mining. Second, we used interviews with gold miners to select mining sites that had been abandoned at different times. We used ecological methods to compare vegetation among these sites to adjacent old-growth forest to estimate forest regeneration following the abandonment of gold mining sites.

Modelling mining-induced deforestation over time

We estimated the total area mined annually in Suriname using anthropological and economic descriptions of the Suriname small-scale gold mining industry. The relevant variables included the number of active gold miners in Suriname today, the average size of mining pits, the area worked per mining team per year, and the amount of re-mining that took place. Our figures are based on information from Suriname officials and on our own observations and measurements in the mining area.

We collected information on historical gold mining activity in the Sella Creek area through qualitative interviews with tribal gold miners in their language, Ndjuka. We interviewed local miners with a long history in the area about the times of mine abandonment and the timing of changes in mining technology. Miners were interviewed independently from one another. We cross-checked the historic data for each site with accounts from different gold miners. This approach was possible because miners typically work in teams of six pit workers and a supervisor at each site. For the most recently abandoned site we relied on personal observations from earlier in that year. Moreover, as explained below, the oldest mine site was abandoned four years prior to our research, therefore many of the miners who had worked at that site were still present in the mining region and were able to recall accurately events from the recent past.

We obtained estimates of gold production and the number of people involved in mining from various governmental officials and mining experts. These people included associates of the Geological Mining Service, the Central Bank of Suriname, and the Suriname offices of the Organization of American States. These estimates were more varied than the estimates of gold miners, probably due to the lack of data on gold mining available to these officials. We used estimates that were the best supported by data.

The scale of deforestation caused by gold mining appears chiefly driven by the number of people participating in mining and by mining technology. Furthermore, mining is limited by the amount of available gold. Because the present and historic status of relevant variables is poorly known, we use simple models based on informed assumptions to estimate the past and future deforestation caused by gold mining.

Our assumptions are as follows. We expect that the number of gold miners will remain relatively constant over the next decade, even though there may be turn-over within the mining population. We do not expect a decrease in the number of local miners because they appear to respond to impoverishment and a lack of job opportunities, which are likely to persist (Healy 1996). Further, the number of people involved in gold mining may be near its limits. It seems that the migration of Brazilian miners to Suriname has slowed down (Suriname Bureau of Labor, personal communication 1998). The local mining population offers little room for growth because a majority of local men are already gold miners and gender traditions make it unlikely that many more women will enter mining (Heemskerk 2000*b*).

Technology determines both the profitability and ecological impacts of mining. Technical modernization allows lower grade ores to be exploited and mining to be accelerated, both of which result in miners clearing more land. Gold miners at Sella Creek estimated that advances in technique have doubled the amount of gold extracted per person at the research site over the past 25 years. Conversations with miners elsewhere suggest to us that the use of bulldozers and excavators may allow miners to treble their extraction rate per year. We expect that in the near future, the use of more productive technology will increase the impact of gold mining in Suriname. However, we do not expect that the impact of mining will more than double, because heavier equipment is beyond the budget of most miners, and most mining operations in Suriname are already approaching the best mining practices in the Amazon region.

Table 1 The equations that defined our models of mining.

Model	*Equation*
Base	$\text{area mined(year)} = 96/(1+[96/\text{mining}_{1985} - 1] \text{ x } e^{-1.30*(\text{year}-1985)})$
Technology improvement	$\text{area mined(year)} = 192/(1+[192/\text{mining}_{1985} - 1] \text{ x } e^{-0.86*(\text{year}-1985)})$
50% re-mining	$\text{area mined(year)} = 48/(1+[48/\text{mining}_{1985} - 1] \text{ x } e^{-1.25*(\text{year}-1985)})$

We expect that all other variables remain constant. We assume that within the next decade: gold reserves do not give out, large scale mining companies do not enter the area, Suriname will not enforce environmental regulations in the interior, and Suriname will not offer better job alternatives for its forest populations. Unless Suriname experiences radical political and economic change in the near future, our experience in Suriname leads us to believe that these assumptions are reasonable.

We developed three simple alternative models of deforestation. We fitted logistic functions to high, medium, and low estimates of current deforestation. We used a logistic growth model because it is a simple model that incorporates both rapid growth and limits to growth. Our logistic models are based on the assumption that the impact of gold mining grew exponentially and then was limited by one or a combination of factors, such as land, technology, workers, and access. We used a minimized least-squares method, from Microsoft Excel 2000 (Microsoft 2000), to fit these models to our estimates of past and current deforestation caused by gold mining, and estimated the cumulative current and future impact of gold mining. The equations that define our models of mining are presented in Table 1.

Forest regeneration following mine abandonment

The first large mining camp in the Sella region was established about 45 years ago, and since then the area has been mined by many people. The area thus appeared to offer a collection of gold mining sites that had been abandoned for a wide range of periods. However, most sites were not appropriate for the study for two reasons. First, there has been a dramatic change of mining methods and older sites are unrepresentative of current mining impacts. Using data from these sites would bias estimates of forest regeneration. Local miners reported that hydraulic equipment was introduced to Sella in 1992–1993. Since then, the size of pumps has increased continuously. To control for this effect, we only sampled sites that were mined with the currently used 4-inch and 6-inch hydraulic machines, which arrived in 1994.

Second, abandoned gold mining sites are frequently re-mined. The cost and time spent on clearing and prospecting a previously mined site are much less than for a new site. Because gold miners fail to extract an estimated half to two-thirds of the gold in the soil (M.M. Veiga, personal communication 1999), the exploitation of old mining sites is economically viable when mining efficiency improves. Re-mining makes it difficult to find sites that have a simple, known land-use history. Sites that are re-mined may regenerate more slowly due to the cumulative impact of multiple disturbances. We only sampled sites that had been mined once.

Another sampling problem was that mining pits and camp areas frequently overlap. Mining occurs in long strips, with some pits being partly excavated and then abandoned, while other pits are filled in with soil excavated from adjacent pits. Further, in addition to mining pits, mining sites typically include area around the pit that is used to dump waste material (e.g. stones and coarse woody debris), land used for rudimentary agricultural production, and camp space with huts, open space, and trails. The boundaries between these areas are unclear. Local miners assisted us in determining the borders of mining pits and working areas at each site.

The final sample included a series of abandoned mining pits on three mining sites of different ages. The oldest site was four years old, and situated near the camp of a miner called Adan (Adan Kampu, AK). The second oldest site that we selected had been cleared 2.5 years ago, and abandoned 1.5 years ago, by a miner called Jacob (Owru Jacob Kampu, OJK). The third site (Lica Kampu, LK) had been abandoned for only 0.2 years. As a control we sampled five separate sets of plots in nearby old-growth forest that were apparently free of anthropogenic disturbance, and were located at least 50 m from trails and camps. Local miners helped us determine the operation dates and the numbers of mining pits and machines that had been used at each site (Table 2). Though we tried to minimize cross-site differences in surrounding forest and the pre-mining vegetation, such differences may have produced bias.

Table 2 Mining-history features of sampled sites (LK = Lica Kampu, OJK = Ourra Jacob Kampu, AK = Adan Kampu).

Site features	*LK*	*OJK*	*AK*
Years abandoned	0.2	1.5–2.5	4
Number of pits at site	3.0	12	8
Duration of mining (years)	0.3	1	1
Number of machines used	1.0	3	1

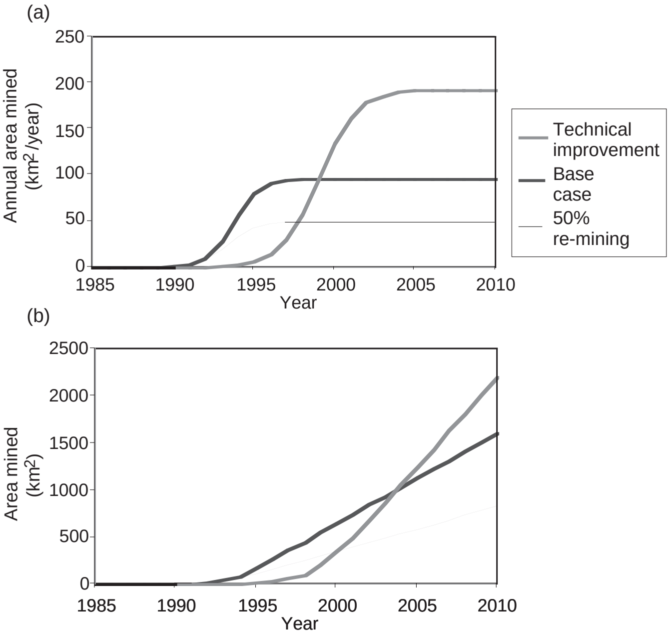

Figure 3 Alternate models of the annual deforestation produced by goldmining in Suriname. These models are based upon fitting linear growth and logistic growth functions to the current deforestation rate and the gold mining rate prior to the beginning of the gold mining boom in 1986. (*a*) Changes in deforestation rate over time. (*b*) Cumulative deforestation over time.

Measuring forest regrowth following mine abandonment

We measured and mapped each mining site, dividing each site into subsections of open water, bare ground, grass and vines, secondary growth, and coarse woody debris (Fig. 3). We characterized the vegetation in each site in more detail by using circular sample plots (1 m radius, 3.14 m^2) along a stratified set of transects. We estimated the ground cover within the circular plots visually, distinguishing trees, open water, sand and rocks, coarse woody debris, grass, vines, ferns and herbs, tree resprouts and regeneration, and leaf litter. In addition, we recorded canopy coverage for each sample plot.

The characteristics of sites were compared using one-way ANOVA. Prior to analysis, per cent vegetation cover data were arcsine transformed (Sokal & Rohlf 1995). Mean vegetation cover was compared among sites using Scheffé's multiple comparison test (Hicks 1993). To assess change on a finer scale, we used the same methods to compare cover among the bare ground, woody debris, and grass subsections of the sites.

Results

In the following section of the paper we present our estimates of deforestation produced by small-scale gold miners in Suriname. We then describe rates of forest regrowth found at abandoned mining sites.

Current deforestation

The current mining population in Suriname was estimated to be 15 000 people, of whom about 12 000 were actively mining at any time. Informed estimates of the number of gold miners present in Suriname range between 10 000–20 000, with most experts accepting an estimate of 15 000 (Ramcharan 1996; Veiga 1997*b*; De Kom *et al.* 1998; Pollack *et al.* 1998). From observation and conversation with gold miners, we estimate that Maroon gold miners on average devoted seven months in the year to participation in gold mining. Brazilian miners spent about 11 months annually on gold mining. This works out to an average of 80% of the total mining population being active at any time, which is equivalent to 12 000 full-time miners.

A mining team typically consisted of a camp operator, six pit workers, and a cook. We observed that each team included, on average, two extra service personnel (e.g. carriers, carpenters), which means that there were about 10 people per team. During a year of research in the area we observed that it took six weeks for a mining team that used one set of equipment to mine a pit. Toward the end of the dry seasons, when hydraulic equipment could not be used in many places due to a lack of water, there was no mining for about one month. Based on these observations, miners were estimated to mine 8 pits yr^{-1}. This rate corresponds to the estimates of local miners. We used these estimates to calculate that 9600 small-scale gold mining pits yr^{-1} were dug in Suriname (Table 3). The average pit size was about 80 m by 80 m. The area surrounding the pit was also cleared and disturbed, bringing the total area disturbed per pit to about 1 ha. These calculations suggest that mining was impacting about 96 km^2 yr^{-1} in Suriname (Table 3).

Not all of the 96 km^2 of mining activity was taking place in old-growth forest because old mine sites were frequently re-mined. Miners have been found to re-mine tailings (Godoy 1985), but how much small-scale mining takes place on old sites versus new locations, in this case old-growth forest, has not been estimated. From observations and communications with local miners, we estimate that about half of the mining occurred on previously-mined sites. If this rate applies to Suriname as a whole, it reduces our estimate of deforestation of old-growth forest to 48 km^2 yr^{-1}. Our estimates of forest clearing per person are higher than estimates reported by retired miners and in earlier studies (Cleary 1990; Bezerra *et al.* 1996). Further we observed that miners using more advanced equipment in other mining areas in Suriname cleared more forest per person. These comparisons suggest that as mining technology develops, miners clear more land per person per year.

Past and future deforestation

Based on mining information from miners and governmental sources in Suriname, we believe that the gold mining boom grew from background levels in 1980 to reach current levels in 1999. In 1980, gold production was estimated to be 5.4 kg yr^{-1} (G. Gemerts, personal communication 1996). We assume that gold mining began to grow logistically after 1985, to reach current rates of about 10 000–12 000 kg yr^{-1} (Heemskerk 2000*a*). The base logistic model assumes that the growth in deforestation plateaus at current levels of 96 km^2 yr^{-1} (Fig. 3). The technological improvement model projects that deforestation continues to increase to plateau at twice this rate (192 km^2 yr^{-1}) (Fig. 3). The third model assumes that half of the mining effort is spent on re-mining old sites while technology remains constant; in this case the area mined reached a maximum of 48 km^2 yr^{-1} (Fig. 3).

Forest regrowth following mine abandonment

Changes among sites

We found large differences in vegetation cover between the mined sites and forest, but differences among the abandoned mining areas were small (Table 4). The sites were significantly different for all vegetation cover types ($p < 0.001$).

Table 3 Definition and quantification of model variables.

Variable	*Definition*	*Quantity*
Gold miners	Total number of gold miners	15 000
Active mining population	Total number of people actively participating in gold mining at a given time (80% efficiency).	12 000
Number of mining machines	Total number of mining machines in use, assuming ten gold miners per machine.	1200
Time used for one pit	Amount of time necessary to mine a pit for a team of 6 people using one mining machine	6 weeks
Number of pits/yr	Number of pits created annually by 1 machine	8
Total pits/yr	Number of pits created annually by all machines in use in Suriname (number of mining machines × pits/mining machine/yr)	9600
Pit size	Average measured size of a mining pit	80 m × 80 m
Cleared area	The total area deforested by mining at one site	1 ha
Total area mined	Total area mined annually in Suriname at the present mining intensity (cleared area/pit × number of pits/yr)	96 km^2
Proportion re-mined	Percentage area being mined on previously mined areas rather than in newly cleared forest	50%
Deforestation	Total area being mined in old-growth forest annually (proportion re-mined × total area mined)	48 km^2

Table 4 Mean (±SE) percentage cover by selected vegetation types on different abandoned mining sites and in old-growth forest.

Vegetation	*LK*	*OJK*	*AK*	*Old-growth forest*
	34	*73*	*78*	*25*
Bare ground	28.1 ± 2.3	40.7 ± 4.6	22.0 ± 2.1	0.7 ± 0.7
Grass	0.0 ± 0.0	25.4 ± 3.2	11.1 ± 2.7	0.0 ± 0.0
Vines	1.6 ± 0.7	1.6 ± 1.6	23.6 ± 4.6	2.5 ± 0.5
Woody debris	20.7 ± 3.2	4.3 ± 1.6	4.4 ± 1.5	5.5 ± 0.9
Leaf litter	35.5 ± 3.8	0.0 ± 0.0	11.2 ± 2.7	73.2 ± 2.1
Resprouts and regeneration	3.5 ± 1.4	0.3 ± 0.2	5.5 ± 1.2	16.4 ± 2.0
Ferns and herbs	0.2 ± 0.1	7.4 ± 1.5	2.4 ± 1.1	0.0 ± 0.0
Open water	10.4 ± 0.0	20.3 ± 0.4	19.8 ± 0.0	0.0 ± 0.0
Trees	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.8 ± 1.0

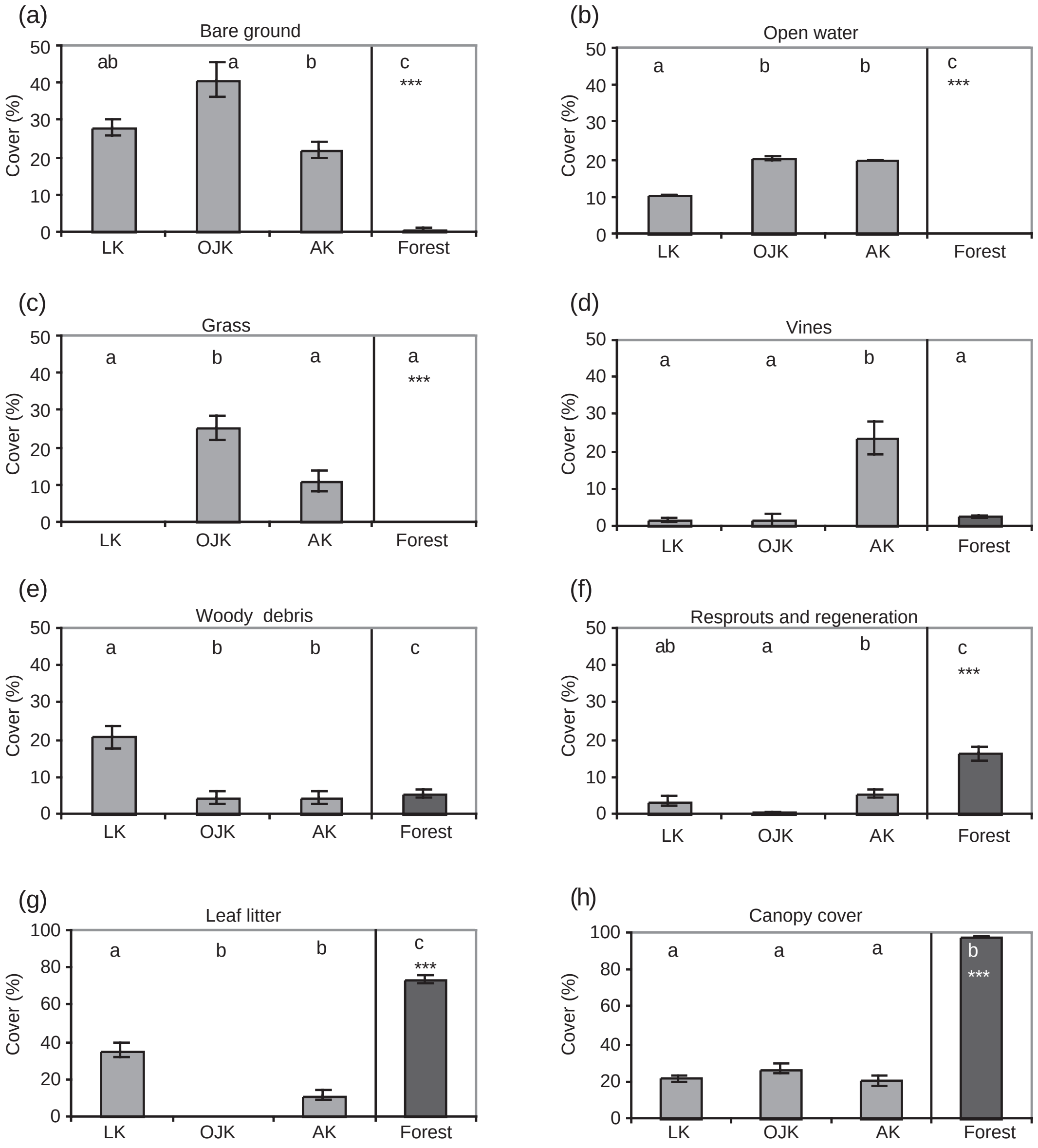

Figure 4 Comparison of abandoned mine sites with nearby forest sites, with respect to: (*a*) bare ground, (*b*) open water, (*c*) grass, (*d*) vines, (*e*) woody debris, (*f*) tree regrowth and regeneration, (*g*) leaf litter, and (*h*) canopy cover. Error bars indicate the standard error of each observation. Different letters above bars indicate significant differences between different sites based upon Scheffé's multiple comparison test ($p < 0.05$).

Even after 4 years, over 20% of the mined area remained bare ground where vegetation had not regenerated (Fig. 4*a*). Substantial areas of open water in mining areas presented another contrast with surrounding forest (Fig. 4*b*). Old mining pits that were not filled in by the residues of more recent mining operations soon became pools of stagnant water. These pools covered 10–20% of the studied mining areas. While tree-fall and erosion had partially filled former mining pits, there was no significant decrease in area or turbidity of pools between the two-year old and four-year old sites.

Grass rapidly invaded sites following abandonment (Fig. 4*c*). Grass was absent from recently mined sites, but covered over 20% of the 1.5–2.5 year old site (OJK). The four year old site (AK) was dominated more by vines than grasses. Vines covered almost a quarter of this site (Fig. 4*d*), suggesting that vines had replaced grasses as time passed. In the nearby old-growth forest, vines were larger and less frequent and grass was virtually absent. Coarse woody debris covered a third of the recently abandoned mine site (LK). The older sites (OJK and AK) contained only about 5% coarse woody debris, the same as in old-growth forest (Fig. 4*e*). We found some tree regeneration on mined sites, but the amount varied. The areas of tree resprouting and tree regeneration at all mined sites remained well below the amounts found in the old-growth forest (Fig. 4*f*).

In old-growth forest, leaf litter covered about 70–80% of the forest floor (Fig. 4*g*). Leaf litter was also quite common at the recently-abandoned mined sites (LK) that were not yet covered with ground vegetation. At the 1.5–2.5 year old site (OJK), leaf litter was scarce. Moreover, this site (OJK) did not have full-grown vegetation that sheds leaves. Leaf fall from secondary growth provided some ground cover at the four year old site (AK), but this cover was not different from the two year old site. Leaf litter cover in the surrounding old-growth forest remained over six times greater.

There were no differences in canopy cover among the mined sites, where canopy cover was below that of the forest sites (Fig. 4*h*). Portions of the mined sites without trees (e.g. bare ground, grass, and standing water) had almost no canopy cover. Canopy cover was highest in those areas that had been cleared but not mined. Neither the total area in secondary growth at each site nor a site's overall canopy cover had increased with time since abandonment.

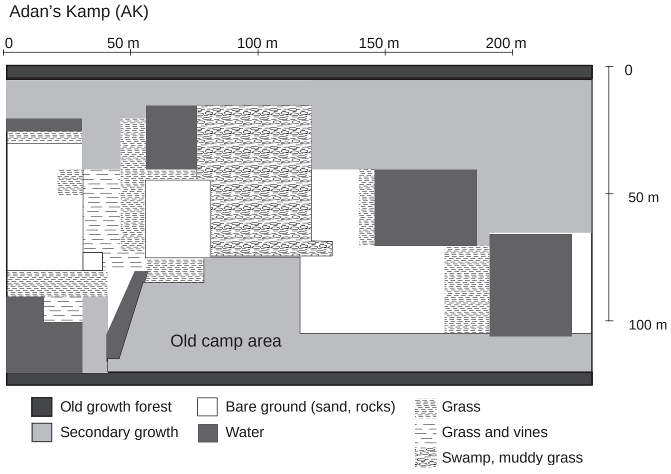

Figure 5 Map of Adan Kampu (AK) gold mining site abandoned about four years prior to sampling. The camp was surrounded by old-growth on the long sides, and connected to other mining areas along the short sides.

Fine-scale change within vegetation types

In addition to comparing the proportional coverage of different vegetation types at each site, we also analysed vegetation cover within each vegetation type. For example, in different sites the large areas characterized as 'grass' included different amounts of herbs, vines, and other plants without being dominated by them (Fig. 5).

The sites that we classified as bare ground remained dominated by bare ground, with little growth of grass, vines or trees (Fig. 6*a*). The bare ground areas of the different mined sites were very similar to each other, and significantly different from forest plots (Table 5). The recently-mined site (LK) did not contain any grass-dominated areas. The other sites did not differ in grass-dominated areas (Table 5). Trees did not appear to resprout in these areas (Fig. 6*b*). The older woody debris site had less woody debris and bare ground and more regeneration, grass, and vines (Table 5). However, these changes were small (Fig. 6*c*). The comparison of changes within vegetation types suggests that areas of bare ground and grass persisted over time while areas of woody debris developed a minimal secondary growth mixed with grass and vines.

Table 5 Vegetation cover differences among the forest and vegetation areas in the abandoned mining sites. Different letters indicate significant differences between sites based upon Scheffé's multiple comparison test ($p < 0.05$).

	Bare ground				*Grass*			*Woody debris and secondary growth*			
	LK	*OJK*	*AK*	*Old*	*OJK*	*AK*	*Old*	*LK*	*OJK*	*AK*	*Old*
n	8	29	31	25	24	27	25	25	25	15	25
Bare ground	a	a	b	c	a	ab	b	a	ab	b	b
Grass and vines	a	ab	a	b	a	a	b	ad	b	c	d
Woody debris	a	ab	ab	a	a	a	a	a	ab	b	b
Leaf litter	a	a	a	b	a	a	b	ab	a	b	c
Tree regeneration	a	a	a	b	a	a	b	a	b	a	a

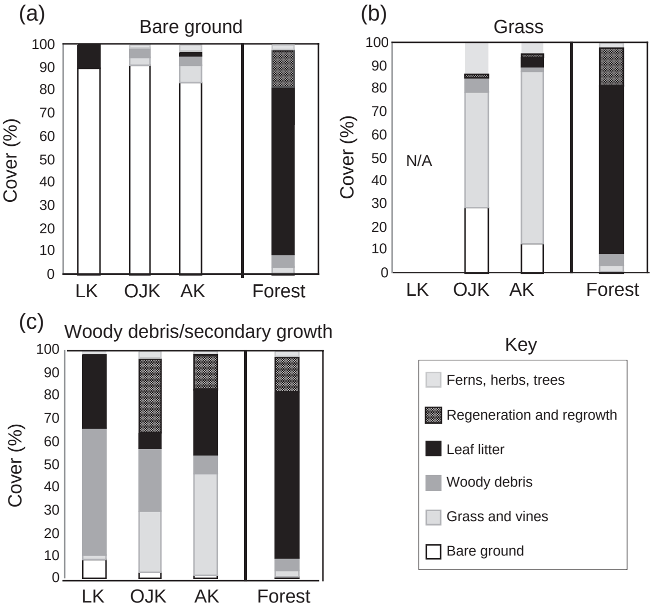

Figure 6 Comparison across sites of fine scale vegetation within vegetation areas classified as: (*a*) bare ground (*b*) grass, and (*c*) woody debris and secondary growth.

Discussion

We estimated that the total area mined annually in Suriname was currently 96 km^2 yr^{-1}. Due to our observations that about half of the gold mining took place on previously mined sites, we suspect that the actual amount of forest cleared by gold miners in Suriname was currently 48–96 km^2 yr^{-1}. While speculative, these are the only data we know of on small-scale mining-induced deforestation in the Amazon.

Based on our models, we suspect that the cumulative mining-induced deforestation from 1980 to 2000 was likely to be 220–390 km^2. Our estimates of cumulative deforestation increasingly diverged into the future, depending on how mining technology changes and on what proportion of mining occurs in old-growth forest. If mining were to continue, we predict that cumulative deforestation would reach 750–2280 km^2 by 2010. The low estimate assumes that re-mining is frequent, and that the total area mined per year has reached a plateau. The high estimate assumes that re-mining is infrequent and that technological improvements will increase the area cleared for gold mining to plateau at double the current levels within five years; true deforestation rates are likely to be somewhere in between.

The 1000 or 2000 km^2 deforested by small-scale miners in Suriname may seem small compared to deforestation by logging, ranching, and other land uses in the Amazon. In the Brazilian Amazon, deforestation primarily from these sources was estimated to be 574 100 km^2 in 1998 alone (Fearnside 1999). However, because the bulk of Suriname's population lives in or near the capital city of Paramaribo, there is relatively little land conversion. Ranching does not take place in the Suriname Amazon, and agriculture and logging have only minimally impacted the region. In the interior there is subsistence agriculture along rivers. Commercial logging has taken place primarily near Suriname's coast (Jonkers 1987). From 1980 to 1995, Suriname's annual deforestation rate was about 150 km^2 (WRI 1999). These figures and our estimates suggest that gold mining is now the main driver of deforestation in Suriname, particularly in the interior.

The area of old-growth forest cleared by gold miners is a small fraction of the total area of Suriname rain forest (147 130 km^2). However, the local impact in gold-bearing regions may be severe. Gold reserves are found in approximately 20 000 km^2 of Eastern Suriname (Veiga 1997*a*), and within this area only small regions can be mined. These regions are primarily near rivers, where most tribal communities are also situated. The consequences of mining for the local populations may be substantial, given that small-scale gold miners stimulate the spread of malaria and sexually-transmitted diseases, cause mercury pollution and the silting of rivers, remove wildlife, and destroy animal habitat.

The vegetation that appears following mining does not resemble the vegetation in adjacent old-growth forest in quantity or quality. Our findings suggest that the regeneration of forest on mined sites is extremely slow. We observed that large areas of mined sites remained bare ground, grass and water, creating kilometres-long corridors of savanna that followed paleo-streambeds. Bare ground was rare in nearby forest and qualitatively different from bare ground at abandoned mine sites, typically consisting of exposed soil on the mounds of leaf cutter ants, rather than the bare rock and sand of the mining sites. Besides large areas of bare ground, substantial areas of grass, vines, and stagnant open water covered mined sites. We found none of these land-cover types in the old-growth forest.

After mining, it seems that leaf litter and woody debris that remained on abandoned mined sites were rapidly replaced by vines, grasses, ferns, and secondary growth. The least impacted portions of mining sites, such as camp areas, and other areas cleared but not mined, were the areas in which vegetation regenerated. These areas had begun to develop secondary forest and deposit leaf litter, but this was a minimal amount compared to that in nearby old-growth forest. Their positioning next to old mining pits is likely to slow down the recovery of cleared but unmined areas, as bare abandoned pit areas reduce the presence of vegetation and animal life that could colonize the site.

Persistent areas of grass, vines, bare ground and water maintain a bright, hot, dry environment that probably inhibits tree regeneration on mined areas. Indeed, within the central portions of mined sites where the mining pits were situated, no regeneration occurred except on soil attached to the upturned roots of fallen trees and in the shaded areas surrounding large pieces of woody debris. Even after several years, tree seedlings, resprouts, and canopy coverage were all but absent from large proportions of mined areas.

Comparison of mining with other landuses

Studies of regeneration following other types of land-use in the Amazon have indicated much faster forest recovery than we found for mining. A study of regeneration of forest gaps in Suriname found that secondary vegetation was quickly established (Shulz 1960). Though herbs and grasses initially dominated regeneration, pioneer tree species, such as *Cecropia* spp., *Inga* spp. and *Vismia* spp., usually reached heights over 10m within two years. Also in Suriname, Boerboom (1975) cleared several plots and found different regeneration rates, depending on the soil structure and the severity of treatment. *Cecropia* 8–11 m high had invaded most sites within 1.5–4 years. Only on the most severely disturbed site with the poorest soil did the pioneer species take seven years to establish. A study in neighbouring French Guyana found that intense fire and a lack of drainage decreased regeneration, while coarse woody debris, seeds and the fact of being close to the forest border accelerated regeneration (Maury-Lechon 1991). Only 6% of the soil surface was bare after 3.5 years, while after six years no bare soil remained.

In Venezuela, Uhl *et al.* (1981) found that surface conditions (i.e., slash, bare soil, roots) had a considerable effect on seedling establishment on a cleared forest site. Depending on the soil type, *Cecropia ficifolia* reached heights of 12 m between 2–6 years after burning. Another study in Venezuela found that a small, cleared and burned forest plot was dominated by *Cecropia* spp. during the second year (Uhl & Jordan 1984). After four years there was a canopy dominated by *Vismia* spp. Uhl (1987) reported that a 0.15 ha site had a partially-closed canopy of *Vismia* at a height of about 8 m after 2–3 years. These findings agree with our observations of regeneration following slash-and-burn agriculture in Suriname forest near mining areas. Cultivators typically did not remove all the trees from a plot, scarcely disturbed the soil, and cleared an area less than a quarter of the size of a single mining pit. Within 1–2 years after clearance, agricultural plots had an open canopy and substantial regeneration, both from pioneer species such as *Cecropia* spp. and from resprouting trees and palms.

In the above examples, cleared plots regenerated forest canopy within 1.5–4 years, with the exception of Boerboom's (1975) most severely disturbed sites. In contrast, regeneration of abandoned mining sites was minimal, and the regeneration that did occur was concentrated in the cleared but unmined areas fringing mining pits. The impact of gold mining is probably more severe than other types of disturbance, because in addition to removing the forest miners completely turn over the soil, eliminating seeds, roots, and tree saplings. The absence of tree regeneration within the grass and vine areas suggests that a closed canopy forest will not establish in mined areas for at least ten years after mining. The minor tree coverage, in turn, further inhibits regeneration by offering little shade, soil recovery, or animal habitat. We expect that it will take decades before early succesional forest establishes itself upon ancient pit and sluice box areas.

Conclusions

Small-scale gold mining has substantial long-term effects on the forest cover of areas in the Suriname Amazon where mining is concentrated. The massive repeated soil movement that accompanies mining greatly slows regeneration, and produces vegetation cover that is qualitatively different from that in nearby old-growth forest. We expect that mined sites will remain deforested for at least a decade, if not far longer. The replacement of pioneer species by old-growth forest trees will take much longer, and it may be centuries before the areas where mining pits were situated resemble old-growth forest.

We estimated the present rate of deforestation to be 48–96 $\mathrm{km}^2\ \mathrm{yr}^{-1}$. Based on these rates, and assumptions about developments in the Suriname mining sector, our models suggest that between 750–2280 km^2 of Suriname forest will be lost to small-scale gold mining by the year 2009. Even though deforestation produced by small-scale gold mining is relatively minor compared to other land uses in the Amazon and compared to the Suriname forest as a whole, its impact is severe. Moreover, within Suriname, gold mining is the primary cause of deforestation.

To our knowledge, this study is the first attempt to assess regeneration following mining, and to estimate and predict total deforestation produced by small-scale gold miners in the Amazon region. Further research on impacts of mining would be valuable. We especially encourage research on the long-term ability of the forest to colonize severely disturbed areas, and on whether changes in mining practices could accelerate forest regeneration.

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