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Gold-rush in a forested El Dorado: deforestation leakages and the need for regional cooperation

Camille Dezécache[1,7], Emmanuel Faure[2], Valéry Gond[3], Jean-Michel Salles[4], Ghislain Vieilledent[3,5] and Bruno Hérault[6]

[1] Université de la Guyane, UMR EcoFoG (AgroParistech, CNRS, Cirad, Inra, Université des Antilles, Université de la Guyane), Campus agronomique de Kourou, 97310 Kourou, French Guiana, France
[2] Ecole Normale Supérieure (ENS Ulm), 45 rue d'Ulm, 75005 Paris, France
[3] Cirad, UPR Forêts et Sociétés, 34398 Montpellier, France
[4] CNRS, UMR LAMETA (CNRS, Inra, SupAgro,Université de Montpellier), Campus Inra-SupAgro, Bat.26, 2 Place Viala, 34060 Montpellier Cedex 2, France
[5] JRC, Bio-Economy Unit (JRC.D.1), Joint Research Center of the European Commission, 21027 Ispra, Italy
[6] Cirad, UMR EcoFoG (AgroParistech, CNRS, Cirad, Inra, Université des Antilles, Université de la Guyane), Campus agronomique de Kourou, 97310 Kourou, French Guiana, France
[7] Author to whom any correspondence should be addressed.

E-mail: camille.dezecache@ecofog.gf, efaure@clipper.ens.fr, valery.gond@cirad.fr, jean-michel.salles@supagro.inra.fr, ghislain.vieilledent@cirad.fr **and** bruno.herault@ecofog.gf

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Abstract

Tropical forests of the Guiana Shield are the most affected by gold-mining in South America, experiencing an exponential increase in deforestation since the early 2000's.
Using yearly deforestation data encompassing Guyana, Suriname, French Guiana and the Brazilian State of Amapá, we demonstrated a strong relationship between deforestation due to gold-mining and gold-prices at the regional scale. In order to assess additional drivers of deforestation due to gold-mining, we focused on the national scale and highlighted the heterogeneity of the response to gold-prices under different political contexts. Deforestation due to gold-mining over the Guiana Shield occurs mainly in Guyana and Suriname. On the contrary, past and current repressive policies in Amapá and French Guiana likely contribute to the decorrelation of deforestation and gold prices. In this work, we finally present a case study focusing on French Guiana and Suriname, two neighbouring countries with very different levels of law enforcement against illegal gold-mining. We developed a modelling framework to estimate potential deforestation leakages from French Guiana to Suriname in the border areas. Based on our assumptions, we estimated a decrease in deforestation due to gold-mining of approx. 4 300 hectares in French Guiana and an increase of approx. 12 100 hectares in Suriname in response to the active military repression of illegal gold-mining launched in French Guiana.
Gold-mining in the Guiana Shield provides challenging questions regarding REDD+ implementation. These questions are discussed at the end of this study and are important to policy makers who need to provide sustainable alternative employment to local populations in order to ensure the effectiveness of environmental policies.

1. Introduction

Tropical forests in South America are increasingly threatened by the expansion of gold-mining, boosted by global demand for jewellery, the international financial crisis and associated gold-prices increase (Shafiee and Topal 2010, Asner *et al* 2013, Ayala *et al* 2013). Contrary to agricultural activities such as soybean farming or ranching, gold-mining has received little attention due to its small geographical extent compared to agribusiness (Alvarez-Berríos and Mitchell Aide 2015). However, the recent explosion of gold prices, from less than 300 USD/ounce in 2000 to close to 1 900 USD in 2011, allowed a better profitability of low-grade deposits, thus establishing gold-mining as an emerging economic activity (Hammond *et al* 2007).

Alluvial gold-mining, which is by far the predominant gold-mining method applied within our study area (Rahm *et al* 2015), has dramatic direct and indirect environmental and social consequences: mercury poisoning of populations (de Kom *et al* 1998, Fréry *et al* 2001, Miller *et al* 2003); increased risk of malaria (Pommier de Santi *et al* 2016) and HIV transmission (Palmer *et al* 2002). It is also increasingly contributing to deforestation (Hammond *et al* 2007, Alvarez-Berríos and Mitchell Aide 2015) which we assess in the present article.

The Guiana Shield remains one of the major unfragmented tropical forests worldwide. However, it concentrates 41% of deforestation due to gold-mining occurring in South-America (Alvarez-Berríos and Mitchell Aide 2015). In this region, a strong relationship between gold production and gold prices was already evidenced (Hammond *et al* 2007). However, no focus was made to the national scale, which impedes assessing the potential effect of other factors than prices, such as governance and law enforcement, on gold-mining activity and associated environmental impacts.

We focused on four political entities within the Guiana Shield: Guyana, Suriname, French Guiana and the state of Amapá in Brazil. These entities are all characterized by high forest cover and low deforestation rates (Griscom *et al* 2009), but greatly differs in terms of political status (while Guyana and Suriname are independent countries, French Guiana and Amapá are subdivisions of France and Brazil), environmental governance and contribution of gold-mining to local economy. Such institutional heterogeneity under a similar environmental context makes the Guiana Shield a prime study area to assess the effects of national policies on deforestation due to gold-mining.

In Guyana, 90% of deforestation is attributed to gold-mining (Guyana Forestry Commission and Indufor 2013), which accounts for 20% of Guyanese GDP and 25% of its exports (Miller *et al* 2003). In Suriname, small-scale gold-mining is the major driver of deforestation and an important source of income for 12% of the population (Ayala *et al* 2013). In both cases, the chaotic expansion of small-scale gold-mining remains largely uncontrolled (MacDonald 2016). Since 2002, facing the increasing activity of illegal miners, the French government launched a series of military operations in French Guiana (Colonel Danede 2005, de Rohan *et al* 2011). In Amapá, stricter regulation imposed in the 1990's by Brazil has limited the local expansion of gold-mining but provoked leakages to neighbouring countries (Veiga 1997, WWF Guianas 2012, Ayala *et al* 2013, de Theije 2015).

The objective of the present study is thus to assess regional and national drivers of deforestation due to gold-mining in the Guiana Shield. Assessing gold-mining related deforestation is challenging; both high spatial and temporal resolution data are needed to cope with its small geographical extent and high temporal variability. This has been recently made possible by the publication of yearly deforestation maps by Hansen *et al* (2013). This work thus provides the first long term assessment of deforestation due to gold-mining over the Guianas. First, aligned with the conclusions of Hammond *et al* (2007) at the regional scale, we show that deforestation due to gold-mining is strongly correlated with gold prices, which brings the ability of local countries to efficiently control deforestation into question. Next, a focus on the national scale demonstrates vast differences between the West and East side of the study area. In the West, which consists of Guyana and Suriname, deforestation due to gold-mining has increased a lot during the period of interest. Alternatively, in the East side, which consists of French Guiana and Amapá, deforestation has stagnated due to stricter environmental policies. These results suggests that public policy is likely limiting the gold price effect. Finally, due to the predominantly informal status of gold-mining and the low accessibility of the areas in the rainforest where this practice occurs, deforestation leakages between adjacent territories may easily emerge, such as experienced in Brazil (Veiga 1997, WWF Guianas 2012), and affect national carbon balances. Assuming that the French repressive policy against illegal gold-mining is the main emerging constraint to gold-mining activity during the period of interest and that gold-miners were recently moving from French Guiana to Suriname such as indicated by de Theije (2015), we established a modelling framework able to estimate deforestation leakages which might have been caused by such change in the local political context. Focusing on the East-West contact area, i.e. the boundary between French Guiana and Suriname (figure 1), and based on an extended dataset covering close to 20 years of deforestation derived from existing maps by Hansen *et al* (2013) and maps produced for the purpose of the present study, we estimated deforestation leakages between both countries. Under our model's assumptions, the repressive context in French Guiana and the absence of regional political cooperation for controlling the expansion of gold-mining might have contributed to substantial deforestation leakages from French Guiana to Suriname. We conclude by discussing how gold-mining challenges some corner-stone principles of REDD+ and provide some recommendations for policy makers regarding the efficiency of current national policies against illegal gold-mining activity.

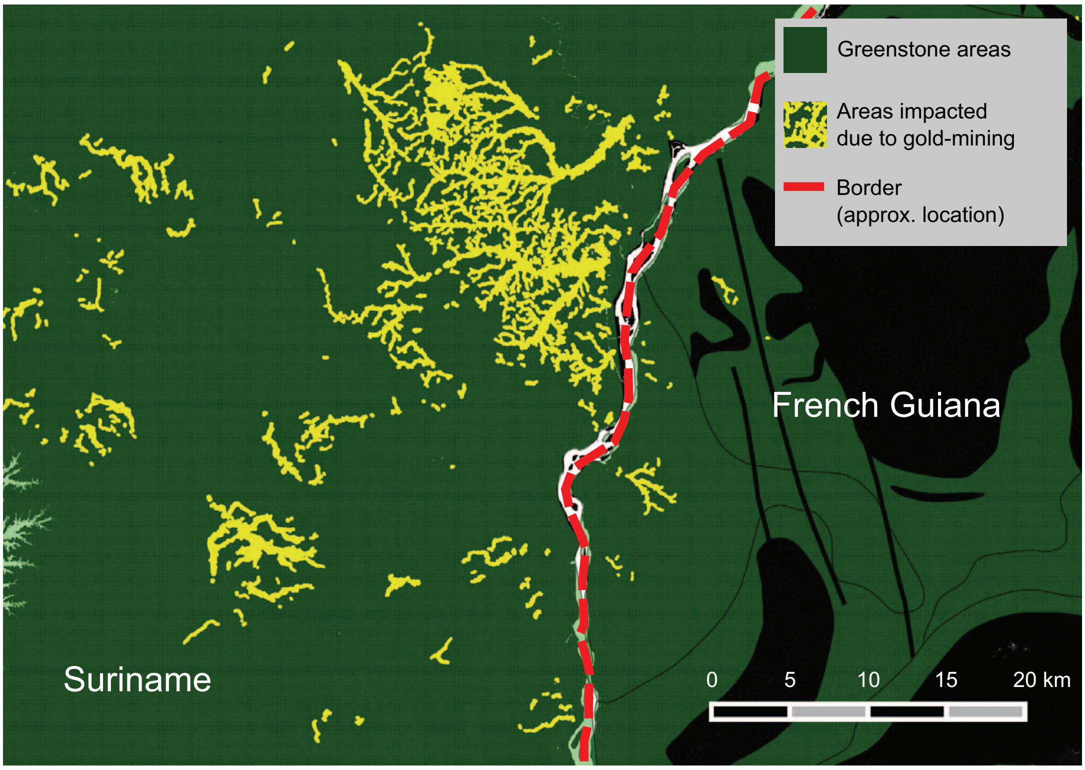

Figure 1. Map of areas impacted by gold-mining in 2014 in French Guiana (right) and Suriname (left). This area corresponds to the blue window displayed in figure 2. Greenstone areas are displayed in green and are present on both sides of the border. Although Greenstone seems less abundant on the French Guiana side, this difference is more likely to be explained by low-quality geological data in Suriname than to an effective difference in Greenstone richness between both countries. Yellow areas, corresponding to the impacts of gold-mining, are much more widespread on the Surinamese side of the border, highlighting the effects of restrictive environmental policy and giving more credibility to a deforestation leakage hypothesis.

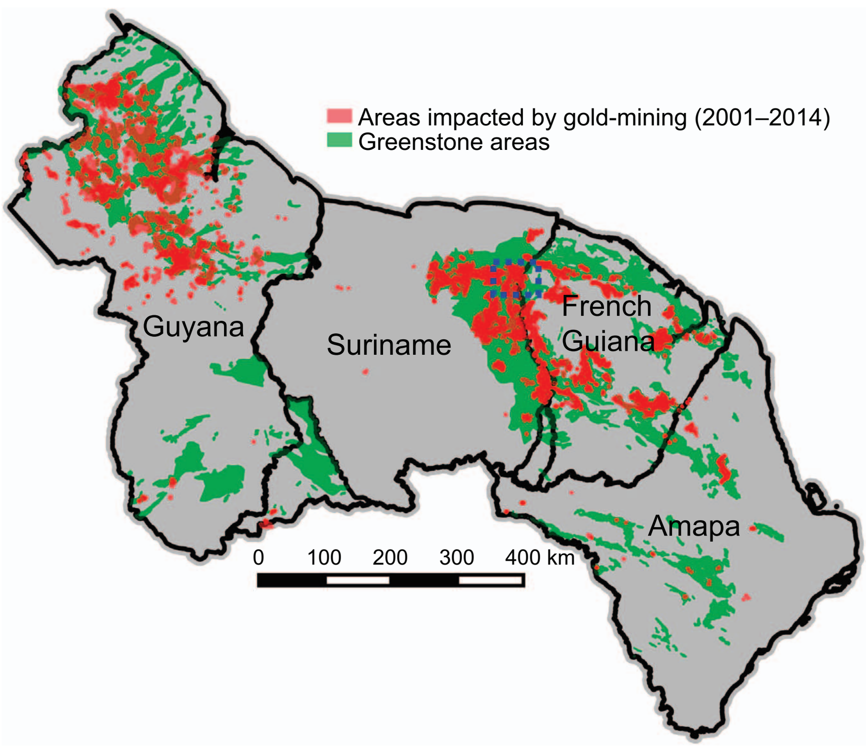

Figure 2. Map of the area of interest which includes Guyana, Suriname, French Guiana and the Brazilian State of Amapá (left to right). Gold-bearing rocks called Greenstone are displayed in green. They concentrate most of the areas impacted by gold-mining in 2014 represented in red. Border conflicts between Guyana and Suriname, and Suriname and French Guiana cause an overlap in the southern parts of these countries. The blue window corresponds to the area covered by figure 1.

2. Material and Methods

2.1. Study area

Our study area includes Guyana, Suriname, French Guiana and the Brazilian State of Amapá. These political entities cover an extent of approximately 600 000 sq. km of which more than 500 000 sq. km are dense tropical rainforests. Gold-mining is closely associated with the presence of a Greenstone formation Hammond *et al* (2007) over the region (figure 2).

Large scale operations coexist with artisanal small-scale gold-mining which is rarely restricted to a few workers using a gold pan. Typically most operations involve the use of excavators and motor-pumps. The introduction of these modern techniques by Brazilian 'garimpeiros' radically modified mining operations (Veiga 1997). Brazilian gold-mine workers spread in the Guiana Shield in the 1990's, when Brazil started to strictly regulate the mining sector (Veiga 1997, WWF Guianas 2012). They constitute a great majority of the gold-mining labour force in the Guianas, with estimates of 75% in Suriname and French Guiana (Heemskerk *et al* 2004).

2.2. Estimating annual deforestation due to gold-mining

Annual deforestation data was derived from deforestation maps by Hansen *et al* (2013) for 2001–2014. Expert-based assessments of areas impacted by gold-mining at the regional scale and at three points in time in 2000, 2008 and 2014 (Debarros and Joubert 2010, Rahm *et al* 2015), in the form of GIS layers, were used to identify deforestation due to gold-mining and exclude other types of activities. Such studies were based on medium to high resolution images, ranging from 5 to 30 meters, consistent with the 30 meters resolution of the maps produced by Hansen *et al* (2013). A previous study by Alvarez-Berríos and Mitchell Aide (2015) used MODIS images at 250 meters resolution and might identify small-scale gold-mining, which is dominant in the Guiana Shield, less accurately (Rahm *et al* 2015).

To avoid excessive inter-annual variability in deforestation due to a potential lag between actual deforestation and its detection by satellites because of clouds, a moving average over three years was calculated and used in following models.

2.3. Large scale VS small scale gold-mining

As it is impossible to distinguish between industrial and artisanal mining from remote sensing data (Rahm *et al* 2015), we weren't able to make such distinction. Using deforested patches size to differentiate large from small mining sites is biased because several neighbouring small mining sites may merge in time into a unique large deforested patch, while the fragmented pattern of gold-mining might represent a large mining site as a succession of small deforested patches. Another way of making this distinction would be to separate open mining pits, which often characterize large-scale mining operations run by multinational companies, from alluvial gold-mining more associated with artisanal activities. Using previously mentioned assessments of areas impacted by gold-mining over the Guiana Shield, we estimated that only about 1% of areas impacted by gold-mining corresponded to open pits likely to be associated with multinationals projects. Given this scarcity, potential biases caused by the contribution of large multinationals' projects are limited, in our opinion. As such, our study *de facto* mainly focuses on alluvial gold-mining, often designated as small-scale gold-mining even when covering several hectares, which we assumed to be operated by a homogeneous set of agents. Such a generalization is of course questionable but preferable under an unclear context. Even in French Guiana, where the level of enforcement is high and the distinction between illegal and legal activities is clear *a priori*, the existence of illegal mining sites very close to legal exploitation permits (Gond and Brognoli 2005) raises the question of potential interactions between legal and illegal spheres.

2.4. Regional model of deforestation due to gold-mining

Hammond *et al* (2007) noted that gold production in the Guiana Shield during 1941–1990 was strongly and positively correlated with gold prices. Assuming that this correlation is still valid in the current context and that deforestation due to gold-mining is proportional to gold production, we modelled deforestation due to gold-mining over 2001–2014 using annual nominal gold-price as the unique explanatory variable. Gold-price was expected to be a strong driver of gold-mining activity, as small-scale gold-miners are usually paid in gold and use it as a means of payment (Heemskerk 2010). The log-normal regional model was formulated as follows:

$$Def_t \sim \ln N(\alpha_0 \times Value_t^{\alpha_V}; \sigma^2_{\text{reg}})$$

where Def_t is the deforestation due to gold-mining over the Guiana Shield at year t in thousands hectares. α_0 and α_V are the model's parameters which we estimated. $Value_t = GoldPrice_t - min(GoldPrice)$, where $GoldPrice_t$ is the mean annual international nominal gold price on global markets at year t, obtained from internet[8], and $min(GoldPrice)$ is the minimum gold price observed over the period of interest, here corresponding to gold price in 2000. We assumed no time lag between changes in gold prices and associated deforestation at a yearly temporal resolution. This is because gold miners are likely to adapt quickly to changing prices. Moreover, as previously mentioned, a moving average over three

[8] http://onlygold.com/Info/Historical-Gold-Prices.asp.

years was calculated for annual deforestation due to gold-mining. For a better modelling consistency, this averaging was also applied to gold prices. This may also tend to hide any time lag between increasing gold prices and increasing deforestation.

From an economic point of view, miners might be more interested in the actual gold price instead of the difference between average gold price at year *t* and gold price at a reference point in time, as we used here. On the contrary, one could argue that economic agents reacts more to differences than to absolute values since differences partially indicate changes in the cost-benefit ratio of gold extraction. From a modelling point of view, using such a difference is more robust; the intercept α_0 corresponds to the amount of deforestation due to gold-mining when prices reached their lowest value during 2001–2014. On the contrary, directly using $GoldPrice_t$ as the explanatory variable would make α_0 uninterpretable, corresponding to the value of deforestation due to gold-mining when gold prices reach a hypothetical null value.

2.5. Testing for a country effect

In the previous section, we assumed a regional determination of deforestation due to gold-mining, with no focus on where miners choose to settle. While they seek to maximize profit, a null hypothesis might assume no difference in production costs between the countries considered, implying that gold miners would spread randomly over the Greenstone Belt. This is supported by the homogeneity in the origin of the labor force mostly coming from a few poor Brazilian States (Heemskerk *et al* 2004, de Theije 2007) and a lack of border controls (de Rohan *et al* 2011). Although such a hypothesis is naïve given the higher level of control of gold-mining in French Guiana and Amapá, as mentioned in our introduction, this simple model allows to test for significant differences between countries with respect to the link between gold price and deforestation.

2.5.1. Estimating national intrinsic gold-mining potential.

Under such hypothesis, all other things being equal, more gold-miners are likely to settle in countries with larger Greenstone areas, so that we used the extent of Greenstone in million hectares as a proxy for the national mining potential. Shapefiles for Greenstone areas were manually digitized using the geological map produced by the Guyana Geology and Mines Commission in Guyana; obtained from the Surinamese forest office (SBB) in Suriname; from the French Geological Survey (BRGM) in French Guiana; and provided by the Scientific and Technological Research Institute (IEPA) in Amapá. Some Greenstone areas are likely to be more accessible by roads or rivers than others; however, we didn't consider this remoteness effect. Indeed, the presence of gold-mining activities in very remote areas, or of remains of the past exploitation of balata gum several kilometers away from any navigable river in French Guiana (Parc Amazonien de Guyane 2015), tend to indicate that the tenacity of those exploiting the natural resources overcomes any accessibility issue.

A more complete estimator of gold-mining potential was constructed based on spatial modelling, considering not only the presence of Greenstone but also the proximity to rivers which by definition are indispensable to alluvial gold-mining (Dezécache *et al* 2017). Based on this spatial model, a value of gold-mining potential was estimated for every pixel of the area of interest, the sum of all pixels over each country providing a national index of gold-mining potential. However, this index was correlated with the national extent of Greenstone ($R^2 > 0.97$). We thus assumed that this latter variable provided a simple and straightforward proxy to estimate the mining potential. Details about this modelled gold-mining potential are described as Supplementary Materials (SM1 stacks.iop.org/ERL/12/034013).

Other variables might seem relevant to explain the intensity of deforestation such as poverty level or the lack of better job opportunities in each of the four entities considered, which were the two major motivations given by gold-miners in a survey by Heemskerk (2002). However, given that a great majority of gold miners are Brazilian (Heemskerk *et al* 2004), mostly coming from the poor States of Pará and Maranhão (de Theije 2007), we excluded those variables in this study. Indeed, if unemployment and poverty in Guyana, Suriname, French Guiana or Amapá could give incentives to local populations to involve in gold-mining, the omnipresence of Brazilian miners indicates that the economic situation of the States from which they emigrate is probably more relevant than the economic indicators corresponding to the political entities of the Guianas.

2.5.2. National model of deforestation due to gold-mining.

The model of deforestation due to gold-mining considering country effect was nested into the regional model and formulated as follows:

$$Def_{t,c} \sim \ln N(\beta_{0,c} \times Value_t^{\beta_{V,c}} \times GMPotential_c; \sigma^2_{\text{nat}})$$

where β are the estimated model's parameters, with an additional index *c* corresponding to each individual country or political entity: Guyana, Suriname, French Guiana or Amapá, and $GMPotential_c$ is the extent of Greenstone in country *c* in million hectares.

2.6. Deforestation leakages between French Guiana and Suriname

2.6.1. The contribution of law enforcement against illegal mining.

In addition to the widespread presence of Greenstone and Brazilian miners in the Guiana Shield, a necessary refinement of the previous models presented above should include the contribution of law enforcement which limits the expansion of illegal gold-mining. Indeed, the launch of multiple military operations against illegal gold-mining since 2002 in French Guiana radically changed the political landscape with respect to gold-mining in the Guiana Shield (de Rohan *et al* 2011), while informal gold-mining remains largely uncontrolled in Suriname and Guyana (MacDonald 2016).

We thus hypothesized that the main emerging constraint to small-scale informal gold-production during the period of interest was the cost associated with the military repression against illegal gold-mining in French Guiana. This policy hinders gold-miner profits, which are reduced by gold seizure, and increase production costs with the destruction of production factors which need to be replaced. As an example, in 2004, the total value of gold and production factors seized reached 16 million euros corresponding to the value of 1 800 kilograms of gold (Colonel Danede 2005).

Based on the experience of movements of gold-miners from Brazil to French Guiana observed in the 90's, especially after the violent repression of gold-miners by Brazilian police in the Serra Pelada mine (de Rohan *et al* 2011), we made the assumption that a same movement was occurring between French Guiana and neighbouring Suriname due to the repressive policy launched in 2002 in French Guiana. Such a hypothesis is also supported by the literature, indicating recent migrations streams between gold fields of French Guiana and Suriname in response to stronger law enforcement and repression (de Theije 2015). Although leakages can also affect Guyana, we considered that the accessibility of Surinamese mining areas from French Guiana by just crossing the Maroni River supported our choice to assume the existence of leakages from French Guiana to Suriname only. By leakages, we consider here deforestation which would have occur in French Guiana but occurs in Suriname due to the movement of gold miners in response to the French repressive policy against illegal gold-mining.

2.6.2. *Leakages model.*

The model of deforestation due to gold-mining and leakages between Suriname and French Guiana was formulated as follows:

$$Def_{t,c} \sim \ln N(\gamma_{0,c} \times Value_t^{\gamma_V} \times I_c \times Repression_t^{\gamma_R}; \sigma^2_{\text{leak}})$$

where γ are the model's parameters. $Repression_t$, the scaled number of illegal miners' shelters destroyed by the army in French Guiana (see SM2 for more details on the construction of this variable) was used as a proxy for the intensity of the repressive policy. In order to take into account the inertia of the repressive effect, i.e. the fact that an intense repression a given year might deter new gold-mining activities for some years later, $Repression_t$ was averaged over a three-year period, between $t-2$ and t. This three-year period was chosen based on preliminary models' results, giving better statistical significance than shorter or longer periods. I_c is a dummy variable taking value -1 for French Guiana and $+1$ for Suriname. This variable considers the negative expected effect of repressive policies on deforestation due to gold-mining in French Guiana, and positive in Suriname.

Gold-mining potential was similar in both countries and was excluded from the model. In the absence of military repression, we hypothesized a similar relationship between prices and deforestation in both countries, which explains the unique parameter γ_V used for both French Guiana and Suriname.

This model assumes a multiplicative effect of the French repressive policy, as shown by the use of multiplication signs. In concrete terms, we assume that changing policies are not displacing a certain amount of gold-mining activity from a country to another symmetrically, which would be expressed in an additive model, but rather translocating the whole process from French Guiana to Suriname, provoking an amplification of gold-mining in the later. Although questionable, such a hypothesis is credible considering that more gold-miners emigrating might create opportunities for economies of scale and more intense logistic flows of production factors, provoking non-linear changes in gold-mining activity.

After setting $Repression_t$ to 0 for each year, we could estimate a counter-factual scenario, in a similar way as a reference scenarios could be built to estimate avoided deforestation under a REDD+ like mechanism.

2.6.3. *Extending the dataset from 1996*

To test the hypothesis of deforestation leakages between Suriname and French Guiana, we extended the deforestation dataset to include the range 1996–2000 for both countries. This allowed us to know more about what was occurring before the beginning of the repressive policy.

67 Landsat 5 scenes were used, covering the extent of gold-mining areas in 2000. Forest cover was classified using Random Forest algorithm (Breiman 2001), known for its good accuracy (Grinand *et al* 2013). Forest cover maps were built for 1996, 1997, 1998 and 1999, and compared to create yearly deforestation maps until 2000. More details on the methodology used for forest cover classification and to ensure homogeneity with the Hansen dataset are provided as supplementary materials (SM3).

2.7. Bayesian inference

The models parameters described above were estimated using Bayesian inference in a MCMC scheme. Compared to frequentist inference, this allowed us to restrict the range and distribution of values of each parameter to realistic intervals. Priors are given in

Table 1. Priors and estimators of the models' parameters. Priors distributions are uniform, denoted *U*(a, b), a and b corresponding to the lower and upper bounds of each distribution respectively. Indices A, FG, G and S stand for Amapá, French Guiana, Guyana and Suriname respectively. σ is the standard deviation of each model. Start values are used in the first iteration of the Metropolis loop, with a jump value indicated between parentheses corresponding to the standard deviation of the proposal function. The parameters estimators listed are the one maximizing the likelihood of the models, with corresponding 95% confidence intervals indicated between bracket.

Model	Parameter	Prior	Start value (jumps)	Estimator	95% CI
Regional	α_0	*U*(0, 5)	1 (0.1)	0.63	[0.53; 0.71]
	α_V	*U*(0, 5)	1 (0.25)	1.83	[0.65; 2.03]
	σ_{reg}	*U*(0, 10)	1 (0.01)	0.09	[0.08; 0.18]
National	$\beta_{0,A}$	*U*(−5, 5)	0.5 (0.05)	−3.86	[−4.02; −3.73]
	$\beta_{0,FG}$	*U*(−5, 5)	0.5 (0.05)	−0.92	[−1.10; −0.80]
	$\beta_{0,G}$	*U*(−5, 5)	0.5 (0.05)	−2.17	[−2.34; −2.02]
	$\beta_{0,S}$	*U*(−5, 5)	0.5 (0.05)	−1.40	[−1.59; −1.29]
	$\beta_{V,A}$	*U*(−5, 5)	0.5 (0.1)	0.32	[0.03; 0.61]
	$\beta_{V,FG}$	*U*(−5, 5)	0.5 (0.1)	−0.78	[−0.94; −0.38]
	$\beta_{V,G}$	*U*(−5, 5)	1 (0.1)	2.47	[2.16; 2.76]
	$\beta_{V,S}$	*U*(−5, 5)	1 (0.1)	2.21	[1.95; 2.55]
	σ_{nat}	*U*(0, 10)	0.5 (0.01)	0.16	[0.15; 0.22]
Leakages	$\gamma_{0,FG}$	*U*(−10, 10)	0.5 (0.1)	−0.58	[−0.75; −0.41]
	$\gamma_{0,S}$	*U*(−10, 10)	0.5 (0.1)	−0.18	[−0.35; 0.01]
	γ_V	*U*(0, 10)	0.1 (0.1)	0.88	[0.62; 1.15]
	γ_R	*U*(0, 10)	0.1 (0.1)	1.25	[0.88; 1.61]
	σ_{leak}	*U*(0, 10)	1 (0.05)	0.28	[0.25; 0.39]

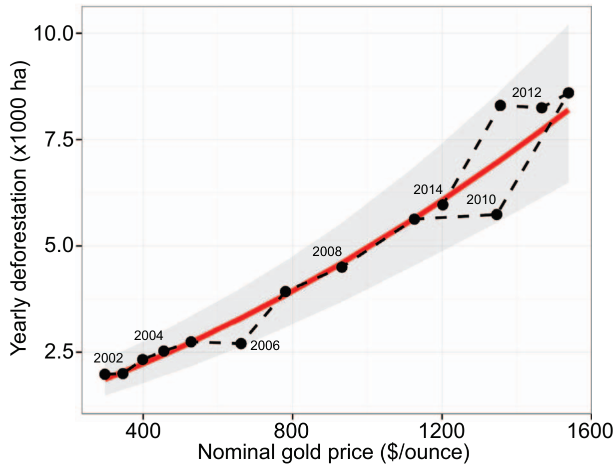

Figure 3. Graphical representation of the regional model of yearly deforestation due to gold-mining over the Guiana Shield in linear scale for the period 2001–2014. Yearly deforestation and mean annual nominal gold price were averaged over a three-year window. Black dots are observed values displayed along a temporal trajectory, associated with corresponding labels for even years, showing a strong increase in deforestation with increasing gold prices followed by a sharp decrease in both deforestation and gold prices at the end of the period. Mean predictions correspond to the red regression line and the gray envelope display the 95% confidence interval.

table 1. 50 000 iterations were computed for each model. 10 000 runs were excluded as burning periods.

All data processing was accomplished via the free and open-source softwares GRASS GIS (GRASS Development Team 2015), QGIS (QGIS Development Team 2009) and R (R Core Team 2015).

3. Results

3.1. Regional model of deforestation due to gold-mining

Gold price is a very strong predictor of deforestation due to gold-mining (table 1). Deforestation at the regional scale was close to 2000 hectares per year when gold prices were below 400 USD/ounce, and reached values higher than 8000 hectares annually when prices peaked around 2012. The relationship between both variables is dynamic and valid not only when prices were increasing but also when they sharply decreased at the end of the period (figure 3). Larger variability in deforestation is observed at the end of the period of interest when gold prices reached 1300–1400 USD/ounce. However, this result remained within the 95% confidence interval of our model.

3.2. National model of deforestation due to gold-mining

Country effects are statistically significant and different between each other, except between Suriname and Guyana, showing a great heterogeneity in the

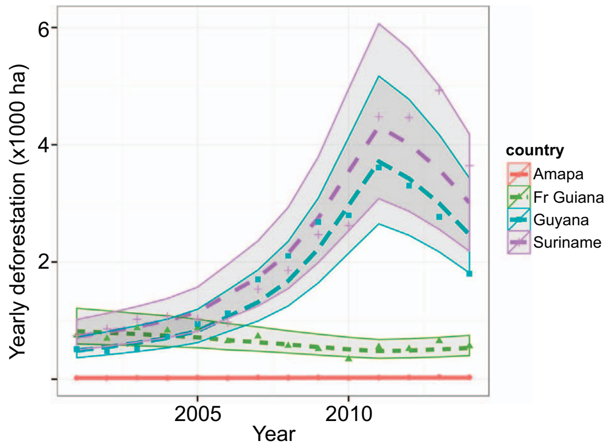

Figure 4. Graphical representation of the national model of yearly deforestation due to gold-mining for 2001–2014. Yearly deforestation and mean annual nominal gold price were averaged over a three years window. Dots correspond to observed values per country, mean predictions correspond to the regressions line associated with a 95% confidence intervals envelope. In Suriname and Guyana, deforestation increased sharply until 2011, boosted by increasing gold-prices, and suddenly dropped when prices started to decrease sharply. This result is contrary to Amapá and French Guiana where deforestation remained at low values during the whole period.

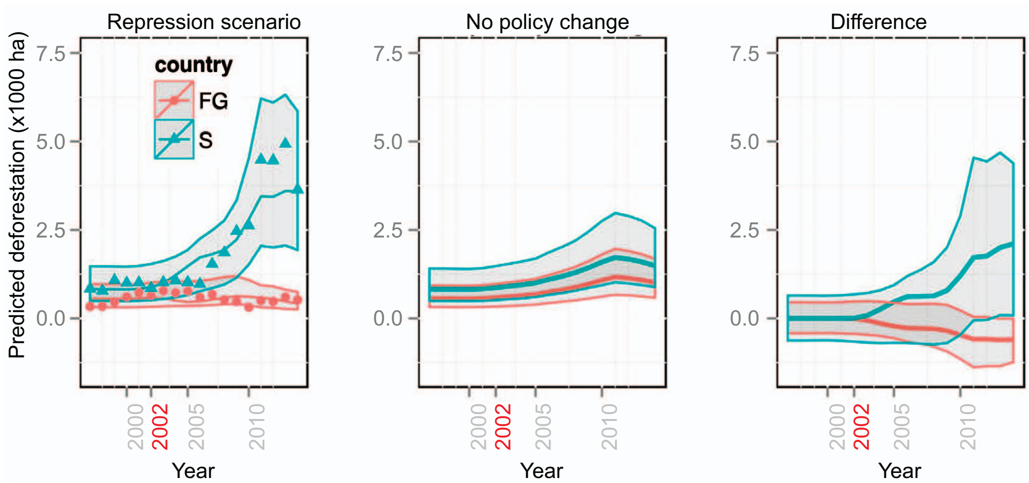

Figure 5. Results of the leakages model calibrated over French Guyana (FG, red) and Suriname (S, blue) over the period 1996–2014. Year 2002, in red, indicates the beginning of the repressive policy against illegal gold-mining in French Guiana. Predicted and observed deforestation under the historical repressive context (left), predictions under a no-policy-change scenario (middle) and the difference between both previous graphs measuring the amount of deforestation leakages (right, negative values indicate a deforestation 'export' while positive values correspond to a deforestation 'import') are displayed, associated with corresponding 95% confidence intervals.

relationship between gold price and national deforestation due to gold-mining (table 1). This relationship is particularly strong in both Suriname ($\beta_{V,S}$ = 2.21 [1.95; 2.55]) and Guyana ($\beta_{V,G}$ = 2.47 [2.16; 2.76]), weak in Amapá ($\beta_{V,A}$ = 0.32 [0.03; 0.61]) and negative in French Guiana ($\beta_{V,FG}$ = −0.78 [−0.94; −0.38]) (figure 4). In Suriname and Guyana, deforestation increased massively until 2011, boosted by gold-prices, and suddenly dropped when prices sharply decreased.

3.3. Case study: deforestation leakages from French Guiana to Suriname

γ_R, the parameter associated with the military repression, is statistically significant and positive (table 1), provoking a decrease in deforestation due to gold-mining in French Guiana and an increase in Suriname.

After removing the part of the model associated with the repressive policy, we could estimate deforestation due to gold-mining in both countries under a hypothetical scenario in which no military repressive policy was launched. Under our modelling hypothesis, policy changes avoided the deforestation of approx. 4 300 hectares in French Guiana over 1996–2014 and increased it by approx. 12100 hectares in Suriname (figure 5).

4. Discussion

4.1. Methodological limitations: the importance of theoretical leakages models formulation

Our leakages model assumed a multiplicative effect of the repressive policy on deforestation. This choice has crucial consequences, meaning that repression is not displacing a fraction of gold-mining activity from French Guiana to Suriname, but exporting the whole process. This explains why the estimated decrease in deforestation in French Guiana and increased deforestation in Suriname are not symmetrical; thus contributing to an amplification of gold-mining in Suriname. This choice may overestimate the effect of repression and underestimate the effect of gold prices. Moreover, multiple leakages are likely to occur in the absence of any border controls, not only to Suriname.

Explanatory variables choice is also critical. Characterizing the intensity of a repressive policy only by counting the number of shelters destroyed is a simplification of the occurring processes. Indeed, this number is not only a function of the intensity of the repressive effort, but also of the number of illegal mining sites under activity or their accessibility.

Finally, in French Guiana, illegal gold-miners tend to exploit smaller alluvial sites or convert to primary gold production (Parc Amazonien de Guyane 2014) which are more difficult to detect by the authorities and provoke less deforestation. Under such repressive context, the link between deforestation and the level of gold-mining activity gets unclear, and deforestation could decrease even if the same number of gold miners are present, provoking biases in deforestation leakages estimation.

For those reasons, we emphasize the need to carefully build leakages models and to interpret the results of our model with care. Field studies could contribute to more precise assessment of the magnitude of deforestation leakages, especially regarding the origin of gold miners in Suriname, while the repressive context in French Guiana *de facto* limits access to illegal mining sites.

4.2. Gold-mining: a challenging case study for REDD+ implementation

All the countries considered in the present study are interested in REDD+ projects. Guyana signed a commitment with Norway to limit its deforestation rates below 0.275% annually (Karsenty and Ongolo 2012). Suriname's Readiness Preparation Proposal was recently approved by the World Bank (van Kanten *et al* 2013). French Guiana, as part of an Annex I country, is not eligible for REDD+, but a domestic project could be an alternative approach (Wemaëre 2014). Amapá is also in a specific situation as part of Brazil, but subnational projects are under construction (Guadalupe Gallardo 2014).

However, our conclusions question three cornerstones of REDD+: additionality, i.e. the proof that avoided deforestation would not have occurred in the absence of any deforestation reduction mechanism, permanence or the guarantee that lands where deforestation was avoided will not be deforested later, and leakages (van Oosterzee *et al* 2012).

Reference scenarios formulation, from which avoided deforestation is estimated, is a major challenge in implementing REDD+ (Huettner *et al* 2009). But formulating a baseline when deforestation is dependent on volatile gold prices is risky. As gold-prices sharply decreased after 2012, deforestation due to gold-mining adjusted downward quasi-instantaneously in Guyana and Suriname: lower deforestation can stem from a less profitable financial context in the absence of efforts, thus contradicting the additionality principle. On the contrary, extremely high prices can limit the efficiency of policies that aim to controlling gold-mining and provoke non-permanence of carbon credits. Indeed, the current repressive policy in French Guiana seems weak by being very careful about protecting the human rights of illegal miners, and thus represents a low threat to them (de Rohan *et al* 2011). It is probably unable to ensure long-term forest protection in case of decreased political willingness to eradicate illegal gold-mining or ever increasing gold prices which would increase the opportunity cost of abandoning gold-mining. On the contrary, the repression of gold-mining in Brazil in the 90's seems still to be effective in deterring miners to exploit gold in Amapá. Little is known about this Brazilian policy, but violent military interventions by the military police were reported, such as in the Serra Pelada mining pit in Pará State, where several small-scale miners were killed (Hoogbergen and Kruijt 2004, Memorial da Democracia 2016). Besides its long-term efficiency, it is thus very unlikely and undesirable that such a policy would be applied elsewhere. Finally, leakages make baseline even more unreliable, due to the multiple interactions between national environmental policies.

4.3. The need for a regional policy against illegal gold-mining

Our national model of deforestation due to gold-mining showed a negative relationship between deforestation due to gold-mining and gold prices in French Guiana. This is likely explained by the repressive policy against illegal gold-mining. In Amapá, the corresponding coefficient is close to zero. As such, the gold-rush observed in the Guiana Shield is mainly driven by increasing mining pressures in Guyana and Suriname in response to increasing gold prices.

Due to the difficulty of controlling the borders within the Guiana Shield in remote and forested areas, the existence of refuge for gold-miners in countries where no strict law exists impedes local policy to have an impact at a supra-national level, contributing to a permanence of logistic flows, i.e. illegal transportation of gasoline, mercury or other production factors, to countries where law enforcement is stronger, such as observed between Suriname and French Guiana (de Rohan *et al* 2011). In an opposite direction, massive gold smuggling from Guyana and French Guiana to

Suriname are suspected (Heemskerk 2010) due to more favourable taxations in the latter. A displacement of the activity to a neighbouring country is costly in response to stricter law enforcement, but this increased cost is probably too small to completely deter gold-miners from working. A regional policy is the only efficient option for a long-term solution to avoid the devastating consequences of illegal gold-mining, which forms part of the official political agenda of all the countries in our study area (de Rohan *et al* 2011).

Whether it is undertaken for forest carbon preservation within centralized REDD+ projects or to limit the broader environmental, health and social impacts of gold-mining, this policy should embody the complexity of the network of economic agents involved and existing cross-sectoral linkages between gold-mining and other forest uses (Hirons 2013). Police cooperation agreements were signed between Suriname and French Guiana, and French Guiana and Brazil in 2008, but differences in the legal frameworks and the opposition of local politicians as in Amapá are slowing down cooperation (de Rohan *et al* 2011, WWF 2014). Although control and repressive policies are necessary and urgently needed to avoid more environmental disasters, a focus should be given to the preservation and enhancement of the livelihoods of local populations, taking into account their preferences while ensuring sustainable alternative jobs creation (Hirons 2011). Such a policy should also encompass neighbouring Brazilian States. Indeed, if local Maroon communities are involved in gold-mining directly or indirectly (Heemskerk *et al* 2004), a large majority of gold-miners are Brazilians, with estimates between 65% and 75% (Heemskerk *et al* 2004, Legg *et al* 2015), 90% of them coming from the rural States of Pará and Maranhão in Northern Brazil (de Theije 2007). This deagrarianisation situation and seasonal migrations adds even more complexity to the gold-mining issue in the Guianas and elsewhere, but must be dealt with by governments and the international community in order to provide efficient ways of limiting environmental degradation and resulting carbon emissions.

5. Conclusion

Gold-mining is an increasing threat to the yet undisturbed tropical forests of the Guiana Shield. Using recently published deforestation maps at high temporal and spatial resolutions, we showed a strong association between gold prices and deforestation due to gold-mining at the regional scale. Although this correlation is worrisome for the implementation of appropriate policies on the longer term due to prices volatility, the variability of the response to price changes among the four political entities considered indicates that a strong political willingness to limit the uncontrolled expansion of informal or illegal gold-mining can be locally effective. However, in the absence of regional cooperation, the existence of deforestation leakages, for which estimates are provided for the first time in this study, greatly reduces the overall performance of isolated national policies. Such leakages are a critical obstacle to the implementation of REDD+ mechanism, but reinforce the need to fully assess the complexity of the socio-economic processes leading to deforestation and to ensure sustainable livelihoods to local populations, which is a necessary pre-requisite to the additionality and permanence of eventual carbon credits.

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