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Accelerated losses of protected forests from gold mining in the Peruvian Amazon

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Abstract

Gold mining in Amazonia involves forest removal, soil excavation, and the use of liquid mercury, which together pose a major threat to biodiversity, water quality, forest carbon stocks, and human health. Within the global biodiversity hotspot of Madre de Dios, Peru, gold mining has continued despite numerous 2012 government decrees and enforcement actions against it. Mining is now also thought to have entered federally protected areas, but the rates of miner encroachment are unknown. Here, we utilize high-resolution remote sensing to assess annual changes in gold mining extent from 1999 to 2016 throughout the Madre de Dios region, including the high-diversity Tambopata National Reserve and buffer zone. Regionally, gold mining-related losses of forest averaged 4437 ha yr^{-1}. A temporary downward inflection in the annual growth rate of mining-related forest loss following 2012 government action was followed by a near doubling of the deforestation rate from mining in 2013–2014. The total estimated area of gold mining throughout the region increased about 40% between 2012 and 2016, including in the Tambopata National Reserve. Our results reveal an urgent need for more socio-environmental effort and law enforcement action to combat illegal gold mining in the Peruvian Amazon.

Introduction

Mineral soils that underlie tropical forests of the western Amazon basin contain diffusely distributed gold deposits. Extracting this gold, which requires a combination of forest removal, soil pit mining, and the use of liquid mercury, poses a major threat to Amazonian biodiversity, water quality, forest carbon stocks, and human health (Ashe 2012, Asner *et al* 2010, Hammond *et al* 2007). In the southern Peruvian Amazon region of Madre de Dios, a global biodiversity hotspot (Myers *et al* 2000), multiple factors have propelled increasing levels of informal (sometimes called artisanal), and mostly illegal, gold mining. First, the 2008 global recession bolstered gold prices, and Madre de Dios exports about 70% of Peru's artisanal gold production to international markets (Swenson *et al* 2011). Second, paving of the Interoceanic Highway through Madre de Dios greatly increased roadway access to forests and prime gold mining sites (Asner *et al* 2010). Third, there continues to be out-migration of people

from Andean regions, such as Arequipa, Cuzco and Puno, to the lowland Peruvian Amazon in regions such as Madre de Dios. Fourth, social and economic pressure to prospect for gold has led to increased organization among miners, supported by local and regional political leaders, which has protected miner activities (Fraser 2009).

Using a combination of airborne and satellite monitoring techniques, Asner *et al* (2013) provided the first high-resolution accounting of gold mining in Madre de Dios. They reported a 400% increase in forest loss generated by gold mining between 1999 and 2012, reaching a total of nearly 50 000 ha of forest removed by 2012. At that time, more than 50% of gold mines were small (< 1 ha) clandestine operations often hidden from main river ways, such as on former river meanders that are now forested.

In response to forest losses and associated social and economic problems, the Peruvian government repeatedly carried out operations around the region to remove miners and destroy their equipment (Defensoría_del_Pueblo 2014, Gardner 2012). The

government also announced numerous legal decrees in 2012 that set in motion actions to regulate the importation and trafficking of gold mining supplies including mercury and fuel (Peru 2012a, Peru 2012b, Peru 2012c, Peru 2012d, Peru 2012e, Peru 2012f, Peru 2012g, Peru 2012h, Peru 2012i).

More recently, advocacy groups have suggested that forest losses from gold mining are underway in a major protected area of Madre de Dios called the Tambopata National Reserve. Such reports have been useful for public outreach (MAAP 2016), but do not provide systematic, multi-temporal analyses of mining encroachment into this important protected area. The Tambopata National Reserve contains more than 3000 recorded plant and animal species, which are organized in multiple and distinct forest types along rivers, in swamps, and on upland *terra firme* (Gentry 1988, Stewart 1988). Forests of the Tambopata National Reserve contain some of the highest biomass stocks in the western Amazon (Asner *et al* 2014), and the watershed is a key freshwater resource for communities downstream of the Reserve, including into Brazil (Thieme *et al* 2007). Gold mining within the Reserve, and within its ecological buffer zone immediately to the north of the Reserve, directly impact these resources, but the rates of miner encroachment are not known. The buffer zone is intended to provide forest access to communities existing before the creation of the Tambopata National Reserve, with the stated intention of preserving livelihoods while ensuring sustainable forest use and conservation measures (Naughton-Treves *et al* 2003). Gold mining within the buffer zone is a well-known problem, but again, the rates and patterns are poorly understood.

Here we utilize a high-resolution remote sensing approach, with timeseries Landsat satellite data, to assess annual changes in gold mining extent from 1999 to 2016 throughout the Madre de Dios region. Using the technique developed by Asner *et al* (2013), we report on regional gold mining-related forest losses, while also focusing on mining within the Tambopata National Reserve and its ecological buffer zone. We seek to understand the long-term rates of gold mining encroachment into these protected and semi-protected regions in the face of new government legislation and programs to reduce illegal gold mining both within and outside of protected areas.

Methods

Study region
The study was conducted in the region of Madre de Dios, Peru throughout a forested area underlain by alluvial soils emanating from the Andes that contain sub-surface gold deposits. This area is bounded on the north side by the Las Piedras River, which incises older *terra firme* substrates containing much less of the alluvial ecosystems containing gold (INGEMMET 2000). The study incorporates the Madre de Dios, Colorado, Puquiri, Inambari, Malinowski, and Tambopata River catchments. In the southern portion of the study area, the Tambopata River lies in the heart of the Tambopata National Reserve, with an ecological buffer zone that runs along the northern border of the Reserve.

Satellite monitoring
We compiled Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) images annually from 1999 to 2016. Annual time-steps of Landsat data were derived by mosaicking four adjacent cloud-free satellite images (path-rows 20–68, 20–69, 30–68, and 30–69) collected during the southwestern Amazonian dry season months of July–September. All imagery has a nominal spatial resolution (ground sampling distance) of 30 m. The data were converted to top-of-atmosphere radiance and apparent surface reflectance using CLASlite (Asner *et al* 2009). The reflectance data were then automatically analyzed for sub-pixel fractional cover of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and bare substrate (S) using the Automated Monte Carlo Unmixing (AutoMCU) algorithm (Asner and Heidebrecht 2002) embedded within CLASlite. AutoMCU has been described in detail (Asner *et al* 2009), and has been extensively utilized to map tropical forest disturbance and deforestation (Bryan *et al* 2013, Lui and Coomes 2015, Reimer *et al* 2015).

The fractional cover data, along with CLASlite's water detection results, were classified to areas comprised of gold mining and/or clearings closely associated with gold mining (e.g. small clearings with miner huts and tents) using the protocols described by Asner *et al* (2013). In this past work, it was found that gold mining generates in a spectrally-unique combination of bare substrate and standing water that results from rain-filling of mining pits. Our decision tree for gold mining was based on the presence of at least 25% bare substrate (for mining, this includes bare soil and sand, tents and other human-made objects) and standing water within each Landsat pixel. The previous study spanning 1999–2012 was fully validated using high-resolution airborne imagery and field observations. Additionally, we verified the 2015–2016 results against higher-resolution Sentinel-2 and WorldView satellite imagery available for the region. In Asner *et al* (2013), gold mine detection omission and commission rates were found to be 15% and 18%, respectively, which is well within the limits required to map gold mining expansion over time. Other non-forest areas not classified as mining sites, such as cattle pastures and agricultural fields, contain spatial mixtures of photosynthetic, non-photosynthetic, and bare substrate cover that greatly differ from that of gold mining. We also masked out river and lake surfaces not associated with mining activities to ensure that they were not mistaken for water-inundated, post-gold mining areas.

Following development of the annual gold mining maps from 1999 through 2016, we tabulated the results at the regional level, as well as for the Tambopata National Reserve and its buffer zone. The Reserve and buffer zone were declared in 2000, and the Reserve has IUCN Category 4 status described as a 'protected area with sustainable use of natural resources'. This designation was originally assigned to protect biodiversity and water resources while fostering pre-existing indigenous use of the area and managed ecotourism. The buffer zone provides a transition between unprotected and protected areas, intended to allow for resource use by communities (mainly comprised of indigenous people and cattle ranchers) that existed prior to the 2000 designation of the National Reserve.

Results

The maps of gold mining activities revealed extensive and temporally progressive forest loss throughout the region (figure 1). Observed mining activities were heavily concentrated within 10 km of the Madre de Dios river and its tributaries—the Colorado and Inambari, and on the Malinowski (heavily mined) and Tambopata (lightly mined) rivers. The data indicated areas of intensive past mining activity, such as in the sub-regions of Huepetuhe (pre-1999), Delta-1 (2008–2011), and Guacamayo (2006–2009) landscapes, among others. However, thousands of widely-spread, small-scale operations have rapidly expanded since 2011, as shown in yellow, orange and red colors of figure 1.

Map-based analyses led to three region-wide findings. First, about 9408 ha of forest had already been mined by the start of our time-series analysis in 1999 (figure 2). Most of this early mining was centered in the Huepetuhe district. Second, mining-related losses in forest cover have varied in intensity each year, from a low of about 1000 ha yr^{-1} in 1999–2000 to a high of nearly 8000 ha yr^{-1} in 2013–2014. Third, despite long-term interannual variability in forest loss, the average (± s.d.) rate of deforestation since 2000 has been 4437 (1440) ha yr^{-1}, with relatively lower rates in 2006–2009, 2012–2013, and 2014–2016 Notably, the downward inflection in the annual growth rate of mining-related forest loss following government action in 2012–2013, was met with a near doubling of the rate in 2013–2014 (figure 2). The total estimated area of gold mining throughout the region in 2016 was 68 228 ha, representing a 40% increase since 2012.

Focusing on the Tambopata National Reserve and buffer zone (figure 3), we discovered that most of the new gold mines were established between 2012 to 2016, although we also found that some small mines had been established long ago. For example, in the 1999 map, we counted only 7 ha of mining within the Tambopata National Reserve (figures 3(b)−(c) and 4(a)). However, from 2000–2001, we found the maximum gold mining-related forest loss of 89 ha within the Reserve (figure 4(a)). Moreover, direct

mining-related losses in the Reserve have averaged 37 ha yr^{-1} (s.d.=25 ha yr^{-1}) since 2000. Critically, however, the protected area underwent a 37% increase in mining-related forest loss since 2012, at a 4 year average rate of 51+12 ha yr^{-1}. As of October 2016, a total of 521 ha of forest have been lost to gold mining within the Reserve.

The buffer zone of the Tambopata National Reserve underwent even greater losses throughout our time period of analysis, totaling 30 047 ha by October 2016 (figure 3). By 1999, 7457 ha of forest in the buffer zone had already been lost to gold mining (figure 4(b)). We also found that mining-related losses in the buffer zone generally increased since 1999 (figure 4(b)), with early years (pre-2010) averaging about 1000 ha yr^{-1}, but more recent years (since 2012) doubling that rate at 2044 ha yr^{-1}. Mining-related deforestation in the buffer zone accounted for 44% of total mining throughout Madre de Dios since 1999.

Discussion

The Peruvian Amazon is part of the highest biodiversity region in the global tropics, which includes forests of Colombia, Ecuador, Peru, and Bolivia (Myers *et al* 2000). Within this biodiversity hotspot, the southern Peruvian Amazon, particularly within the Madre de Dios region, boasts the world's highest recorded levels of animal diversity (Mongabay 2016). The Tambopata National Reserve is a major part of the biodiversity hotspot within Madre de Dios, containing many thousands of recorded plant and animal species, and likely many more that are currently undescribed (Stewart 1988). Informal gold mining removes all forest species and the organic soil horizons underlying them (Malm 1998, Swenson *et al* 2011), and it leads to waters polluted by mercury-laden sediment, both within mining sites and suspended in rivers downstream (Limbong *et al* 2003). Mining thus represents a direct and ecologically extreme threat to the region, its protected areas, and thousands of species including humans.

We found that the geographic extent of informal gold mining has continued to increase in Madre de Dios since 1999, and it has done so at an increasing rate, despite numerous government legal decrees and police actions. At the regional level, we calculated an overall increase in mining extent of 40% since 2012, the year in which many of these legal decrees were put into action. In late 2011, Law No. 29815 (Peru 2011) gave the first federal executive power to legislate in matters of illegal mining, including the interdictions of illegal mining and fight against crime associated with illegal mining. One of the most important contributions of this law is the distinction between informal and illegal mining, with the purpose of applying different legal consequences to each case. Illegal mining is, by definition, the mining that takes place in prohibited areas such as federally protected areas, or the use of equipment or machinery not permitted and/or
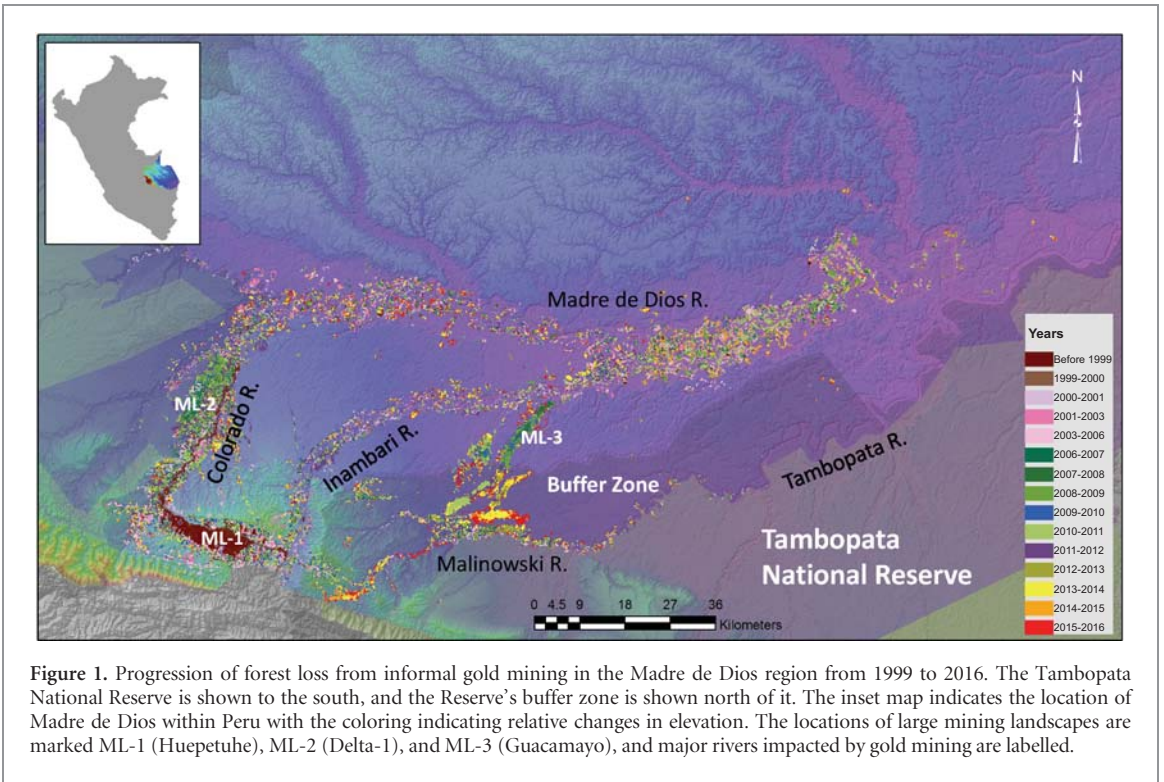
Figure 1. Progression of forest loss from informal gold mining in the Madre de Dios region from 1999 to 2016. The Tambopata National Reserve is shown to the south, and the Reserve's buffer zone is shown north of it. The inset map indicates the location of Madre de Dios within Peru with the coloring indicating relative changes in elevation. The locations of large mining landscapes are marked ML-1 (Huepetuhe), ML-2 (Delta-1), and ML-3 (Guacamayo), and major rivers impacted by gold mining are labelled.
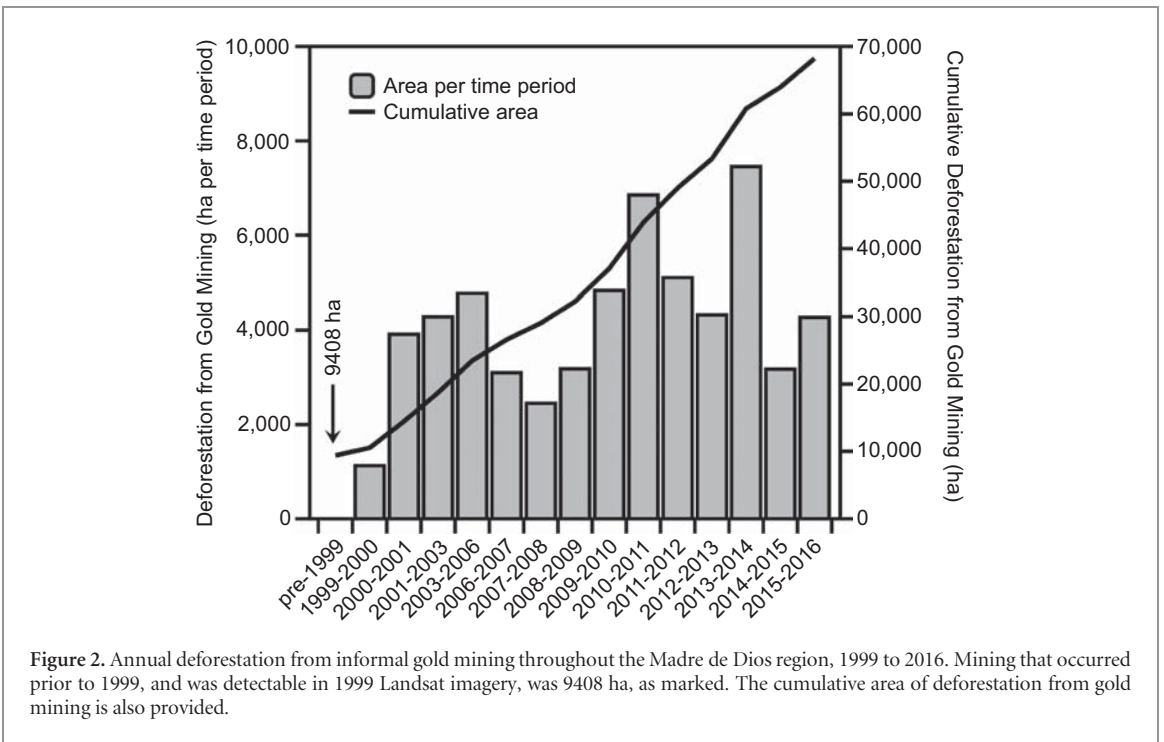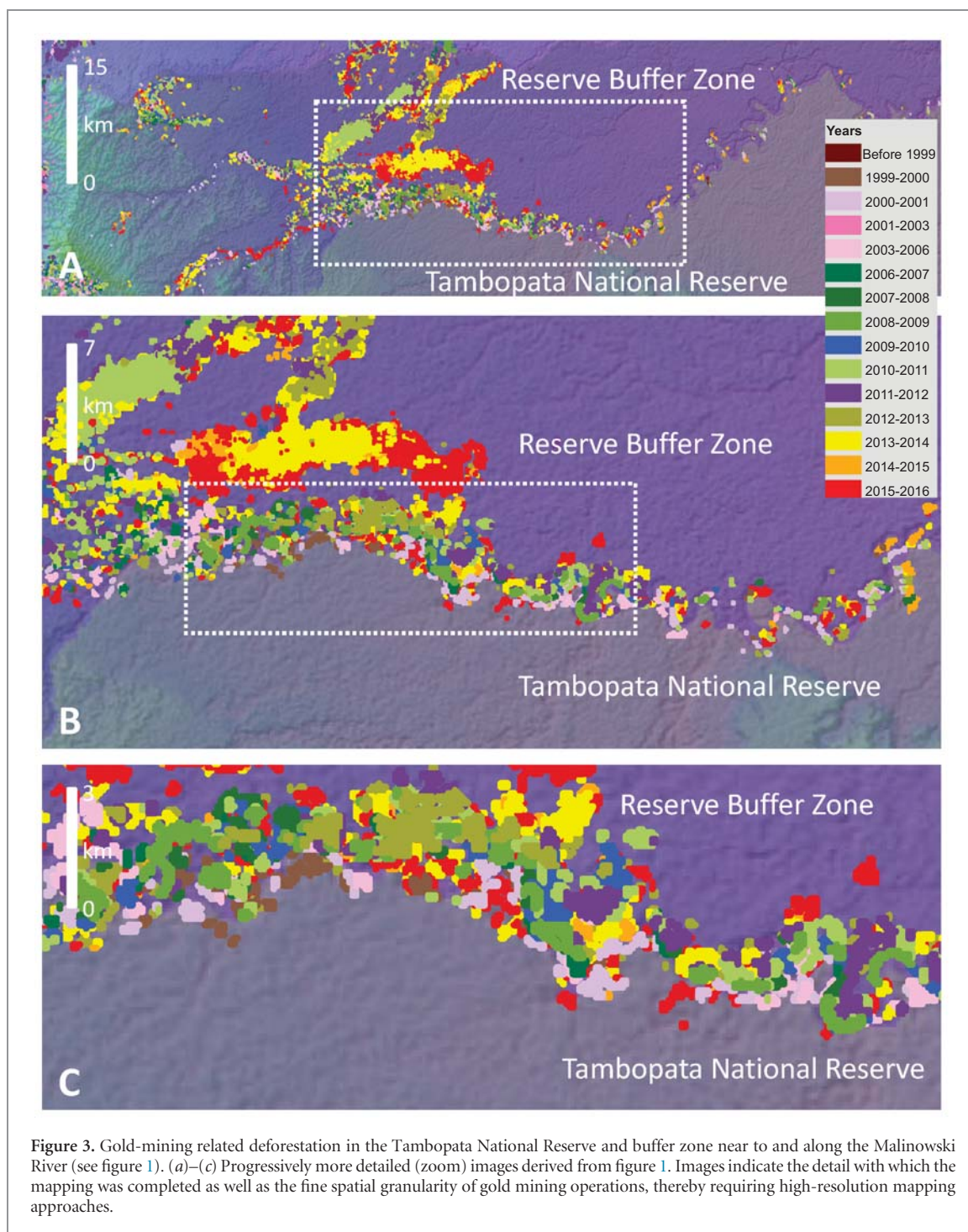

Figure 2. Annual deforestation from informal gold mining throughout the Madre de Dios region, 1999 to 2016. Mining that occurred prior to 1999, and was detectable in 1999 Landsat imagery, was 9408 ha, as marked. The cumulative area of deforestation from gold mining is also provided.

without meeting administrative, labor and environmental requirements.

Based on Law No. 29815, a series of measures issued by the government in 2012 established illegal mining offenses, and initiated the fight against money laundering and other crimes related to illegal mining (Peru 2012a, Peru 2012g, Peru 2012h). Interdictions were also established to enhance control of illegal mining (Peru 2012i). A national strategy for the interdiction for illegal mining has as its main goal to prioritize interdiction zones, among which is the buffer zone of the Tambopata National Reserve. Additionally, the 2012 legal measures included the control of the distribution, transport and commercialization of chemical inputs and equipment used for gold mining, especially mercury, potassium cyanide and sodium cyanide that damages human health and the environment (Peru 2012d, Peru 2012e). However, despite the interdictions that are said to have eradicated 90% of miners in the buffer zone in 2012–2013, which was apparent in our

Figure 3. Gold-mining related deforestation in the Tambopata National Reserve and buffer zone near to and along the Malinowski River (see figure 1). (*a*)–(*c*) Progressively more detailed (zoom) images derived from figure 1. Images indicate the detail with which the mapping was completed as well as the fine spatial granularity of gold mining operations, thereby requiring high-resolution mapping approaches.

mapping results (figures 3 and 4(*b*)), a fast recovery of capacity by the miners to return to or look for new mining areas including the Tambopata Reserve was observed on the ground, which we also detected by 2014 (figures 3 and 4(*b*)). Although losses within the Reserve total a relatively small area of 521 ha, the rate of gold-mining related deforestation within this protected area mirror that of the buffer zone and the region as a whole (figures 2 and 4). We thus expect little abatement of the current trend without further action.

Gold mining is not a recent phenomenon in Madre de Dios: Our results indicate that 9408 ha of mining was detected in 1999, the first year of our mapping study. Moreover, even the Tambopata National Reserve, an area designated for protection and sustainable forest uses such as ecotourism (Kirkby *et al* 2010), had undergone small-scale intrusions of gold mining activities before 1999. Since then, the intensity of gold mining within the Reserve has varied, ranging from low prospecting years such as 2001–2003 and 2011–2012 to much larger intrusions in 2000–2001 and 2012–2016 (figures 3–4). Given the limited length of the time-series thus far, we found it difficult to assess causality behind the inter-annual fluctuations in gold mining expansion. However, reported gold market prices are correlated with mining rates on interannual timescales ($R^2 = 0.43$; $p < 0.05$). Importantly, the average annual rate of illegal mining within the Reserve has been
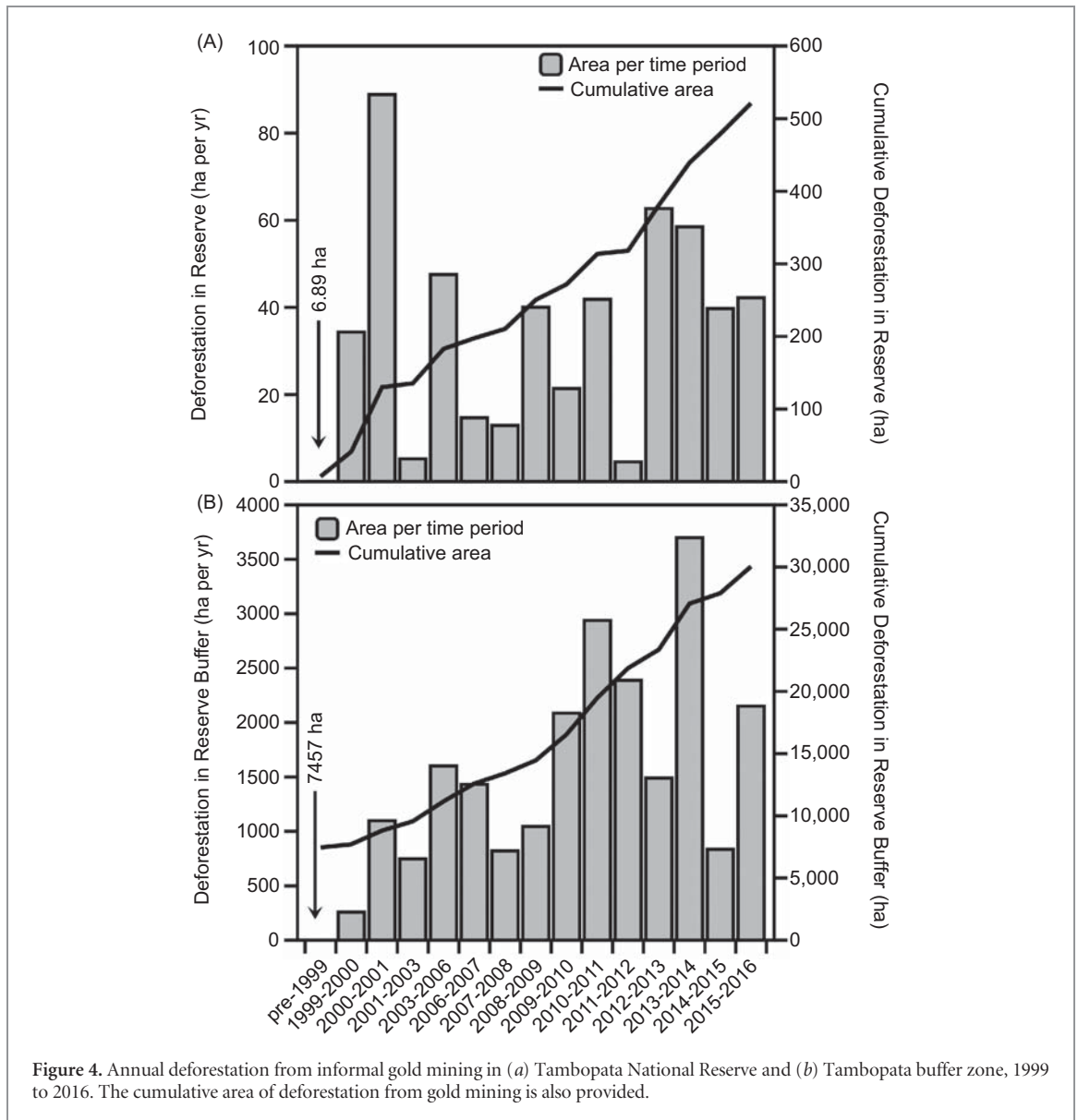
Figure 4. Annual deforestation from informal gold mining in (*a*) Tambopata National Reserve and (*b*) Tambopata buffer zone, 1999 to 2016. The cumulative area of deforestation from gold mining is also provided.

consistently high on a relative basis since 2012, a period following legal and police action against gold mining in the Madre de Dios region.

Gold mining is not a sustainable form of forest use. Once the soils underlying the forests are stripped of gold, miners move on to new forested areas. There are also no known examples of large-scale restoration successes on previously mined landscapes (Román-Dañobeytia *et al* 2015). Even if restoration efforts are undertaken, it will not ameliorate the extreme ecological losses incurred by gold mining in the first place. Compared to other drivers of deforestation, such a cattle ranching, mining presents a worse case ecological scenario that fully removes the composition of the forest down to the mineral soil, and pollutes ecosystems downstream and downriver from mining sites. Unfortunately, gold mining in tropical forested regions continues to rise globally, in similar patterns and with similar consequences as observed in Madre de Dios (Alvarez-Berríos and Aide 2015)

The problem with the enforcement of anti-mining laws rests in the clandestine and nomadic nature of gold mining activities. Unlike fixed land uses following deforestation, such as cattle ranching, miners move on and/or can return to an area following police action. Through this process, the geographic footprint of gold mining continues to shift and expand, despite federal government efforts to contain it. One expression of this rests in the fact that mining now threatens areas designated for protection, such as the Tambopata National Reserve. Only through socio-economic reforms and incentives, coupled with law enforcement, will an abatement of the current trajectory of mining-related forest loss recorded here likely be achieved (Gonzalez 2016, Hilson 2002).

Systematic monitoring of gold mining activities must continue to provide quantitatively robust evidence of change over time. While snapshots of gold mining activities, whether taken as journalistic photographs from aircraft or by high-resolution satellite

imagers, are useful for alerting the public, consistent and temporally comparable data are needed to develop spatially-explicit trajectories of gold mining activities. Quantitatively-robust mapping techniques, such as spectral mixture analysis with Landsat imagery, provide the data needed to support a range of policy and enforcement activities required to address the gold mining problem. In this study, we used CLASlite (Asner *et al* 2009), which utilizes nine different Earth observing satellites including the Landsat and Sentinel series, as well as data archived on the Google Earth Engine (Google 2015), to automatically map forest cover, deforestation and forest degradation. As of May 2017, the freely available CLASlite online training course (Asner 2014), offered in English and Spanish, has been used by individuals from 2805 government and non-government organizations in 137 countries. While the course and software are provided free-of-charge to non-profit government, non-government and academic organizations, using the CLASlite method, like any approach, requires a dedicated technical person (or technician) to lead the analysis. Monitoring gold mining in Peru is a straightforward project for one individual to carry out for her or his organization and for the community. As such, we contend the current limits to stemming the tide of illegal and/or environmentally harmful gold mining is a matter of enforcement, and not monitoring.

Acknowledgments

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