Elevated rates of gold mining in the Amazon revealed through high-resolution monitoring

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Gold mining has rapidly increased in western Amazonia, but the rates and ecological impacts of mining remain poorly known and potentially underestimated. We combined field surveys, airborne mapping, and high-resolution satellite imaging to assess road- and river-based gold mining in the Madre de Dios region of the Peruvian Amazon from 1999 to 2012. In this period, the geographic extent of gold mining increased 400%. The average annual rate of forest loss as a result of gold mining tripled in 2008 following the global economic recession, closely associated with increased gold prices. Small clandestine operations now comprise more than half of all gold mining activities throughout the region. These rates of gold mining are far higher than previous estimates that were based on traditional satellite mapping techniques. Our results prove that gold mining is growing more rapidly than previously thought, and that high-resolution monitoring approaches are required to accurately quantify human impacts on tropical forests.

Carnegie Airborne Observatory | CLASlite | forest degradation | deforestation | Peru

Millions of years of Andean erosion have brought layers of sediment into the vast western lowland Amazonian ecosystems now covered by high-biomass and high-biodiversity tropical forest. Within depositional zones, the subsoils are laced with a diffusely distributed, yet highly enriched amount of gold. Mining the gold that underlies tropical forests poses a threat to biological diversity and to the carbon currently sequestered in the plants and soils covering gold deposits.

Mining for gold has long been undertaken in low-intensity indigenous activities in the Andean foothills and along riverbanks in the Amazon lowlands (1). Gold rushes have also come and gone in the Amazon, sometimes with major ecological and societal impacts (2), but the geographic footprint of these boom-and-bust cycles has never been well documented. In 2008 the world economic recession resulted in a rapid increase in gold prices (3) and a surge of gold mining occurred in the southern Peruvian Region of Madre de Dios. This region supplies more than 70% of the annual gold resource in Peru (4); however, mining activities mostly remain unpermitted by the government. Here we refer to these activities as informal mining operations, and most are illegal.

In an effort to understand gold mining in Madre de Dios, Swenson et al. (5) reported that the three largest mining areas had removed a then alarming 15,500 ha of primary tropical forest by 2009. Their study used free Landsat satellite data with a spatial resolution of 30 m to map these three large mines, one of which was established in the 1980s as the Huepetuhe mine in the Andean foothills. The other two large mines, known as Guacamayo and Delta-1, were established much later. The Guacamayo mine links the Inambari River to the recently paved Interoceanic Highway. The Delta-1 mine lies in previously forested lands between the Colorado and Puquiri Rivers. All three mines rest in areas of very high biological diversity (6) and all are readily visible in Google Earth images. Employing image interpretation techniques widely used in remote sensing, Swenson et al. (5) also estimated a gold-mining-driven deforestation rate of 1,915 ha yr−1 based on the establishment and expansion of these three largest mines. Most importantly, their study correlated an increase in mining activity with market gold prices and with the importation of toxic mercury used in the gold-extraction process.

Although the area of these few large gold mines in the Madre de Dios region has been mapped with Landsat imagery, the geographic extent and ecological impacts of thousands of small mines have gone unexamined because of the extremely clandestine style of these operations and the challenge of mapping them with satellite sensors (Fig. 1). Miners are known to move up and down rivers at high temporal frequency, leaving only subtle signs of their presence in gouged clay terraces and riverbanks that have proven hard to detect or map with satellites. More recently, it was thought that miners are locating their operations back from the main stem of regionally important rivers, such as the Madre de Dios, Colorado, Inambari, Malinowski, and Tambopata, to better conceal their presence from law enforcement and passers-by. However, none of these mining operations have been quantitatively mapped, and thus their individual and combined effects on the ecology of the region remain unknown.

Here we report on a study to map gold mining activities in the Madre de Dios region of Peru using very high-resolution satellite and airborne imaging techniques. We used the Carnegie Landsat Analysis System-lite (CLASlite) (7) to detect and map mining extent in both small and large operations throughout the region. CLASlite differs from other satellite-mapping approaches because it uses spectral mixture analysis to detect changes in forest cover in increments as small as 1% of a Landsat pixel, or about 10 m² (8, 9). This process allows for the detection and

Significance

Commodity gold prices increased substantially following the 2008 global financial crisis. Gold demand has fueled a massive increase in mining activity, some of which is centered in the Amazon basin. Western Amazonian forests of Peru have become an epicenter for mostly illegal gold mining, but the clandestine nature of mining activities has made monitoring and reporting of forest losses extremely challenging. We combined high-resolution satellite and aircraft-based imaging with field surveys to address this issue in one of the highest biodiversity regions on Earth: Madre de Dios, Peru. We found the gold mining extent and rates are far higher than previously reported, with critically important implications for the ecology and environmental policy of this unique tropical rainforest region.


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mapping of fine-scale disturbances that go undetected using traditional remote-sensing methods (10, 11).

We tested the satellite mapping results with two levels of evaluation. First, we carried out an extensive ground-based survey in areas where access and personnel safety risks were acceptably low, to validate the accuracy of the CLASlite results for gold mining detection and classification. Second, we used the Carnegie Airborne Observatory (CAO) (12) to evaluate the accuracy of the CLASlite maps along edges of large mines as well as among the small clandestine mining operations set back from the roads and rivers in the region, which have proven virtually impossible to access on the ground.

Results
Satellite Results. CLASlite results indicated an increase in gold mine extent from less than 10,000 ha in 1999 to more than 50,000 ha by September of 2012 (Fig. 2). We calculated the annual rate of mine expansion, finding that it had tripled from 2,166 ha·yr⁻¹ before the 2008 global economic recession to 6,145 ha·yr⁻¹ after 2008 and through 2012. In this period, the average annual increase in gold mining area was 14%, and this rate peaked at 20% in 2011.

Using field observations and CAO data, we confirmed up to 94% of the CLASlite detections for mines developed in the 2009–2011 period of overlap between datasets (see Field and Airborne Validation, below), leaving only a small residual fraction of suspected but unconfirmed mining operations (Fig. 3A). Importantly, the relative contribution of the three largest mine areas—Huepetuhe, Delta-1, and Guacamayo—to the regional gold mining footprint changed in the period from 1999 to 2012 (Fig. 3B). The largest Huepetuhe mine represented 76% of region-wide mining in 1999, but by 2012, regional mining activity increased to the point in which Huepetuhe only accounted for 21% of total activity (Fig. 3C). In this 13-y period, both the large Delta-1 and the small, diffuse mining operations increased enormously in extent and relative contribution to the region. Delta-1 increased in area by threefold from 1999 to 2012, but the small mines underwent nearly a 600% increase in the same period (Fig. 3). The newest large mine, Guacamayo, emerged in late 2006, increasing to 13% of the total regional mining area by 2012. Zoom image maps reveal thousands of previously undocumented small mines throughout the region (Figs. S1–S3).

Through this approach, we also discovered hundreds of new small mines in the foothills (600- to 800-m elevation above sea level) in the headwater region of the Colorado, Inambari, and Malinowski Rivers (Fig. 4). These “breakouts” of small, upriver mines were confirmed by air in July 2011 and again in September 2013.

Critically, as of 2012 small mining operations constituted 51% of the total mining activity throughout the region (Fig. 3). In other words, the cumulative geographic footprint of the thousands of small, clandestine mines matched the impact of the three well-known, large mining landscapes of Huepetuhe, Delta-1, and Guacamayo. All mining areas, independent of whether they are operated as large or very small extraction sites, greatly increased in overall extent in the 2008–2012 period following the global recession that had led to increased gold prices (Fig. 4).

Field and Airborne Validation. Stratified, random field sampling at 166 locations of small mining operations (< 5 ha) indicated omission and commission errors of 15.7% and 18.0%, respectively (Table 1). The $\kappa$-statistic was 0.64. This result indicated high
reliability of the CLASlite maps for detection, mapping, and monitoring of small gold mines.

Because field-based validation is fraught with uncertainty because of time differences between field and remotely sensed observations—and in our case, extremely dangerous access on the ground—we also used CAO imagery to randomly generate 1,500 points intersecting with CLASlite maps. Formally, this approach is not completely random because the CAO imagery did not constitute wall-to-wall coverage; we focused flights on the large Guacamayo and Huepetuhe mines and along the Madre de Dios and Malinowski Rivers for small mines (Figs. S4–S7). The results indicated omission and commission errors of 5.9% and 7.1%, respectively (Table 1). The κ-statistic was 0.86, indicating very high reliability of CLASlite mine detections against aircraft observations. Close inspection of the airborne data indicated that areas of standing dead trees, often located within 100-200 m of active mining sites, were often not classified as part of the gold mining footprint. This finding was expected given our criteria during CLASlite analysis requiring the presence of bare soil or standing water (Fig. 1 and Fig. S4).

Discussion
Gold mining is rapidly expanding in the western Amazon, with an explosion of activities centered in the Madre de Dios region of Peru. Our results reveal far more forest damage than has been reported in the past, both in terms of the current area affected and the rate of clearing over time. The 50,000 ha of new mining that we mapped from 1999 to 2012 far exceed previous estimates and reports by the government and nongovernment organizations operating in the region. For example, Swenson et al. (5) had estimated about 15,500 ha in total by 2009, whereas we found more than double that amount (32,371 ha) in the same period. The difference in estimates rests in the fact that previous work has focused on the three large mines without accounting for the thousands of small clandestine mines along roads and waterways.

With high-resolution monitoring, we observed an average 6,145 ha·yr⁻¹ of forest loss caused by gold mining after 2008. Deforestation for gold mining now exceeds all other forms of forest loss combined, including ranching, agriculture, and logging (13). Moreover, our rates of mine expansion, combining both small and large mines, are about 40% higher than previous estimates for Madre de Dios. This information has not made it into conservation, resource policy, or law enforcement circles, yet it is critical to multiple ongoing efforts to contain or combat illegal and unsustainable gold mining in the region.

Although 50,000 ha of total loss in 13 y appears small on the scale of other tropical regions undergoing deforestation or forest degradation (e.g., refs. 14 and 15), Madre de Dios is world-renowned for its unusually high biological diversity. A single hectare in the region undergoing gold mining harbors up to 300 tree species, and many more floral and faunal inhabitants (6, 16, 17). Average carbon stocks exceed 100 Mg C ha⁻¹ (13), and the density of top predators, like jaguars and large-bodied...
Gold mining greatly increases sediment loads in rivers, disrupting vast tracts of these critically important aquatic ecosystems (21). At this point in time we do not have sufficient data on the downriver distances negatively affected by heavy sediment loads from mining, but our visual estimates from aircraft suggest that the effects persist for hundreds of kilometers, potentially well into Brazil. Recent quantitative work also shows very widespread mercury pollution in air and waters throughout Madre de Dios, negatively affecting the entire food chain and people far beyond the mining sites (22). Hunting is also widely associated with gold miners who search the forest for game meat, creating empty forests with impaired ecological function, potentially for centuries to come (23, 24). Additionally, we observed widespread tree mortality on the fringes of both small and large mines. Although we do not yet know the precise cause, we speculate that mobilized sediments, anoxic or desiccating conditions, and perhaps heavy metals associated with the mining process, may be killing many more trees than is currently being accounted for in this study.

Our results highlight the central role that high spatial and temporal resolution monitoring must play to understand and address the gold mining problem in the Amazon basin and elsewhere. Without knowing the location and rate of expansion of both small and large mines, the ecological and societal impacts cannot be accurately assessed. Here we found that the largest mines, easily observed from space, now play an increasingly subordinate role in determining the rate and pattern of degradation and the subsequent dismantling of these high-diversity tropical forests. Methods using moderate-to-low resolution satellite sensors originally designed for studies of the climate system, such as the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer, should not be relied upon for monitoring the diffuse yet ubiquitous impacts of humans on tropical forests.

Ironically, it is the original NASA series of satellites designed specifically for land-cover change monitoring, Landsat, which currently provides the best available method for monitoring forest degradation at the global scale. The launch of Landsat 8 in 2013 provided a major boost to the global land-cover change and forest-monitoring communities, and the data are freely available. Despite this advance in preparedness with Landsat, we also have often found that simple classification approaches operating at the whole-pixel scale fail to detect the diffuse canopy disturbances that lead to forest degradation. Whether the source is selective logging or understory fire (10, 25), and now smallholder gold mining shown here, newer approaches based on subpixel spectral mixture analysis of Landsat imagery yields high-fidelity maps that can be used by stakeholders to address the issue of degradation. Forest degradation, which now has 20- to 30-fold impacts in the tropics than does wholesale clear-cutting or deforestation (26), remains an important and accelerating form of forest change throughout the tropics.

Gold underlays vast regions of western Amazonian forests, but it can also be found in many other tropical regions (e.g., refs. 27–29). The widely practiced techniques of gold extraction using surficial prospecting methods augmented with highly toxic mercury leads to proximal impacts on the environment, ranging from biodiversity loss to enhanced carbon emissions, as well as distal effects, such as adjacent forest mortality, defaunation, and polluted fisheries. The demand for gold will likely remain unabated in the foreseeable future, leaving decision-makers with the immediate challenge of implementing containment and mitigation strategies. Any potential long-term solutions will likely require much more active law enforcement to protect tropical forests and waterways, as well as a de-emphasis on the use of gold as a financial commodity.

**Methods**

**Study Region.** We focused the study on the region of Madre de Dios, Peru in an area dominated by Holocene age alluvium containing the highest concentrations of subsurface gold deposits (Fig. 2). This area is bounded on the

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**Fig. 3.** (A) Confirmed and suspected deforestation caused directly by gold mining in the southern Madre de Dios region from 1999 to 2012. (B) Contribution of the three large mines compared with small mines from 1999 to 2012. (C) Relative contribution of large and small mines to the total regional mining footprint over time.
north by the Las Piedras River, which incises older terra firme substrates containing much less of the depositional floodplain ecosystems containing gold (30). To the south of the study area, the Tambopata River lies in the heart of a highly protected area with little gold mining. We also limited the study area to the west of the city of Puerto Maldonado and to the east of the Manu River. We included the Andean foothills in the region known as Quincemil, and to the east and west of that zone. The study region included the Madre de Dios, Colorado, Puquiri, Inambari, Malinowski, and Tambopata River catchments, among others of smaller order.

Satellite Monitoring. We compiled Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus images annually from 1999 to 2012. The annual maps were made into a mosaic from four adjacent cloud-free Landsat images (path-rows 20–68, 20–69, 30–68, and 30–69) collected during the southwestern Amazonian dry season months of July–September for each year of analysis. The data were converted to top-of-atmosphere radiance and apparent surface reflectance using CLASlite (31). The reflectance data were then analyzed for subpixel fractional cover of photosynthetic vegetation, nonphotosynthetic vegetation, and bare substrate using the Automated Monte Carlo Unmixing (AutoMCU) algorithm (32) embedded within CLASlite. The AutoMCU has been described in numerous publications (7) and has been used extensively to map forest disturbance and deforestation worldwide (e.g., refs. 11, 26, 33–35).

The fractional cover data, along with CLASlite’s water-detection results, were classified to areas comprised of gold mining or clearings closely associated with gold mining (e.g., small clearings with miner huts and tents) using a Geographic Information System (ArcGIS 10.0; ESRI). Through a process of examining CLASlite cover fractions against field observations and CAO aircraft imagery, we found that gold mining operations result in unique combinations of bare substrate and standing water that results from rain-filling of mining pits (Fig. 1). Our decision tree for gold mining was based on the presence of at least 25% bare substrate (for mining, includes bare soil and sand, tents, and other human-made objects) and standing water within each Landsat pixel. The resulting subpixel mapping classifications were evaluated using CAO high-resolution imagery and field data. Other nonforest covers not included as mining sites were cattle pastures and agricultural fields that were always comprised of mixtures of photosynthetic vegetation, nonphotosynthetic vegetation, and bare substrate. We also masked out water associated with rivers and natural lakes. We did not include areas of standing dead trees, potentially associated with gold mining areas.

Table 1. Field- and aircraft-based accuracy assessment of gold mining

<table>
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<th>Assessment variable</th>
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<th>Other</th>
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<td>Total</td>
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<td>682</td>
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</tbody>
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*Field work coincided with mining in the 2011–2012 period.
†Aircraft observations were centered on 2009 and 2011 mining activities.

For field-based validation, omission and commission errors are 15.7% and 18.1%, respectively. For aircraft-based observations, omission and commission errors are 5.9% and 7.1%, respectively.

Fig. 4. New deforestation driven by small and large gold mining operations in the years 2008–2012, following the global financial recession and the rapid increase in gold prices.
Airborne Mapping. In 2009, 2011, and 2013, we used the CAO (12) to map portions of the large mines: Guacamayo, Hupepetu, and Delta-1, as well as floodplain, swamp and terra firme forests found along portions of the Madre de Dios, Malinowski, Colorado, and Tambopata Rivers (Figs. S1–S7). We focused CAO data collection on these rivers because they are regionally described as current or potential hotspots of small-scale, clandestine mining activities. We used the CAO light detection and ranging (LiDAR) scanner and visible-to-near infrared (VNIR) imaging spectrometer to assess the accuracy of the CLASLite maps along forest edges. The CAO LiDAR represents a highly accurate way to determine the location of each standing tree at 1.1-m spatial resolution, providing estimation of how well CLASlite defines forest edges and vegetation conditions within the mining areas. The VNIR spectrometer provides 1.1-m resolution optical imaging of deforested patches, which are easily interpretable as mining, infrastructure, agriculture, ranchland, and other surfaces (Fig. 1). For each randomly selected CLASlite pixel, we automatically determined forest versus nonforest cover in the CAO LiDAR data. Then using the spectrometer, we rapidly but manually interpreted each validation pixel to classify as mining or nonmining.

Field Validation. We conducted a field survey over a period of 2 mo in 2012 for small gold mines along the Madre de Dios and Colorado Rivers, as well as on the Interoceroic Highway of southern Peru. A total of 166 points were randomly generated in the Geographical Information System to define locations for the field visits. We observed each point, either by visiting the selected location using a handheld Global Positioning System, or by observing from an oblique angle, classifying the point as a gold mine or no gold mine. The points were spread over a distance of ∼300 km of river and road network, with a buffer of 2 km used to limit the point selection distance from the rivers and road. We recognize that the results of this field work, like most validation field work, cannot be considered as absolute truth, given the challenges of access and interpretation of surrounding vegetation conditions. Nonetheless, the field-validation exercise provided critical feedback for ensuring best-possible estimation of small mine classifications.

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