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Does formalizing artisanal gold mining mitigate environmental
impacts? Deforestation evidence from the Peruvian AmazonNora Álvarez-Berrios^{1,4,*} , Jessica L'Roe^{2,4} and Lisa Naughton-Treves^{3,4} ¹ International Institute of Tropical Forestry, Río Piedras 00926, Puerto Rico² Department of Geography, Middlebury College, Middlebury, VT 05753, United States of America³ Department of Geography, University of Wisconsin, Madison, WI 53706, United States of America⁴ Authors arranged alphabetically.

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E-mail: alvarez.nora@gmail.com**Keywords:** Amazon, biodiversity, land use, land rights, Madre de DiosSupplementary material for this article is available [online](#)**Abstract**

A global surge in 'artisanal' smallscale mining (ASM) threatens biodiverse tropical forests and exposes residents to dangerous levels of mercury. In response, governments and development agencies are investing millions (USD) on ASM *formalization*; registering concessions and demarcating extraction zones to promote regulatory adherence and direct mining away from ecologically sensitive areas. The environmental outcomes of these initiatives are seldom systematically assessed. We examine patterns of mining-related deforestation associated with formalization efforts in a gold-rich region of the Peruvian Amazon. We track changes from 2001 to 2014 when agencies: (a) issued 1701 provisional titles and (b) tried to restrict mining to a >5000 km² 'corridor'. We use fixed-effect regression models and matching methods to control for gold price, geology, and accessibility. Mining increased dramatically during this period, clearing ~40 000 ha of forest. After the mining corridor was declared and enforcement increased, new mining sites were opened more frequently within titled areas and inside the corridor than elsewhere. However, mining also increased in protected area buffer zones and native communities, and the proportion of mining area occurring outside the corridor grew, concentrated in a few hotspots. Interviews ($n = 47$) revealed that the hoped-for regulatory adherence failed to materialize because miners who were issued provisional titles started operations without complying with attendant environmental rules. Overlapping land claims for agriculture and forest extraction proved a major obstacle for obtaining full legal rights to mine. Miners resented the slow, costly formalization process but many sought titles to bolster territorial claims, avoid policing, obtain credit and recruit paying 'guest' miners who generally ignored regulations. We find that responses to formalization varied with changing context and while formalization may curb mining in some circumstances, it may exacerbate it in others. Without adequate enforcement, interagency coordination, and attention to competing land claims, formalizing ASM may accelerate ecological destruction.

1. Introduction

In recent years, artisanal, smallscale mining (ASM) has grown explosively in tropical regions, spurred by soaring gold prices and improved road access [1]. Today, over 40 million people engage in ASM (~16 million mine gold), the majority very poor [2]. Although ASM connotes reliance on informal labor, the terms 'artisanal' and 'smallscale' obscure

the fact that many of these miners are engaged in mechanized, capital-intensive modes of extraction that yield thousands of tons of gold annually, much of it marketed by illegal operators, including criminal syndicates [3]. ASM is associated with appalling labor conditions and severe environmental damage, including deforestation, mercury contamination, and the destruction of ecosystems' capacity to store carbon [4].

Despite the alarming environmental damage [1], most experts conclude that ASM cannot be stopped, only better regulated via formalization [2]. Governance scholars use ‘formalization’ to refer broadly to state-building in remote areas [5]. Here we address formalization more specifically as the process of establishing property rights and zoning unregulated ASM activities. Formalization advocates hope that proffering secure claims to smallscale miners will favor more equitable distribution of profits and fewer labor abuses. Such interventions also promise to shift ‘transient, inefficient, ecologically harmful artisanal mining, to settled, sustainable, small- and medium scale mining’ and ‘limit the ecological impacts to a particular zone’ [2, p 55].

In theory, formalization answers the environmental problems of ASM through three general mechanisms:

- (a) Zoning—Consolidating mining is essential for lowland forest conservation because alluvial mining involves the complete removal of both forest and topsoil [4] and reforestation is very costly and slow [6]. Thus rather than emphasizing forest-friendly practices, formalization efforts aim to confine the activity, decrease downstream impacts, and spare sensitive ecosystems [7].
- (b) Security—A miner with a secure claim is thought less likely to race to exploit a site using the cheapest, most polluting methods and can instead obtain loans to invest in cleaner technology [2]. These expectations grow from a general prediction, based on studies of smallscale agriculturalists, that secure tenure encourages sustainable stewardship of forests [8]—a premise untested for ASM.
- (c) Legibility⁵—A legally recognized and mapped concessionaire becomes more governable [9], i.e. the concessionaire can be held accountable for environmental damage and may be more inclined to adhere to regulations [7]. In fact, *before* they acquire full rights to mine, miners must prove how they will avoid damage.

Critics worry that formalization is more about the state trying to privatize and extract resources than promote sustainable development [5, 10]. They charge that ‘top-down’ ASM formalization benefits elites and marginalizes vulnerable people [11, 12] and can accelerate environmental destruction or simply formalize polluters [10, 13].

Whether formalization mitigates ASM environmental damage is largely untested, partly because it

is notoriously difficult to implement [14]. Smallscale miners often resist formalization, and instead create informal territories through their work and ‘recalcitrant engagement’ [14] with regulations [15, 16]. Crime syndicates use bribes and violence to undermine formalization [3, 17]. Against these forces, few ASM formalization projects are fully realized [13]. Nonetheless, policy makers view ASM formalization as axiomatic and development agencies spend millions (USD) annually on related projects [7, 18]. Thus, despite or perhaps because of the fact that implementation is often flawed [13], the environmental effects of ASM formalization efforts merit systematic study.

1.1. Background on ASM formalization in Madre de Dios, Peru

We examine the relationship between formalization efforts and mining expansion patterns in Madre de Dios (hereafter MdD) in southeastern Peru. Biodiverse, carbon-heavy lowland forest predominates, ~50% of which is under legal protection or within indigenous territories [19–22] (figure 1). Regional deforestation drivers include logging, smallscale agriculture, cattle ranching and mining [20]. In MdD, as elsewhere, the scale of ASM varies, but even small mining operations are typically equipped with hydraulic machinery. After they clear forest, they use water jets to transform the cleared land into a slurry, which they pump into a sieve and hopper. More capitalized operations do the same, but employ heavier machinery, including bulldozers, some worth >\$100 000 [23]. At all scales, sieved ore is mixed with mercury to separate out the gold. Export firms, some criminal, buy the gold and also supply mercury and build roads to mining sites [3].

Miners have panned the area’s gold for generations [5]. ASM expanded during the 1980s and 1990s, driven by national socioeconomic crises and government campaigns. Our study begins in 2001 shortly before Peru passed the *Law of Formalization and Promotion of Small and Artisanal Miners* (table S1 (available online at stacks.iop.org/ERL/16/064052/mmedia)). This law established a protocol for issuing ASM concessions patterned after regulations for companies mining in the Andes [24] (table S1). Obtaining a concession (=full legal right to mine) involves several steps starting with the issuance of a provisional title (hereafter ‘title’) by which individual miners claim a specific area. Before any titled individuals start working, they must show there are no competing land claims, submit an environmental impact study, and obtain permission to cut forest [25, 26] (figure 2).

In the early 2000s, Peru began decentralizing public agencies and promoting regional land-use planning to reduce resource conflicts at extractive frontiers [28]. In MdD, late in 2006, the Regional Office of Energy, Mining, and Hydrocarbon (DREMH) became responsible for encouraging ASM and

⁵ As per J C Scott, we use *legibility* to refer to the way that governments seek to render land and people more governable by fitting them into standardized and ‘visible’ systems like cadasters and censuses [9].

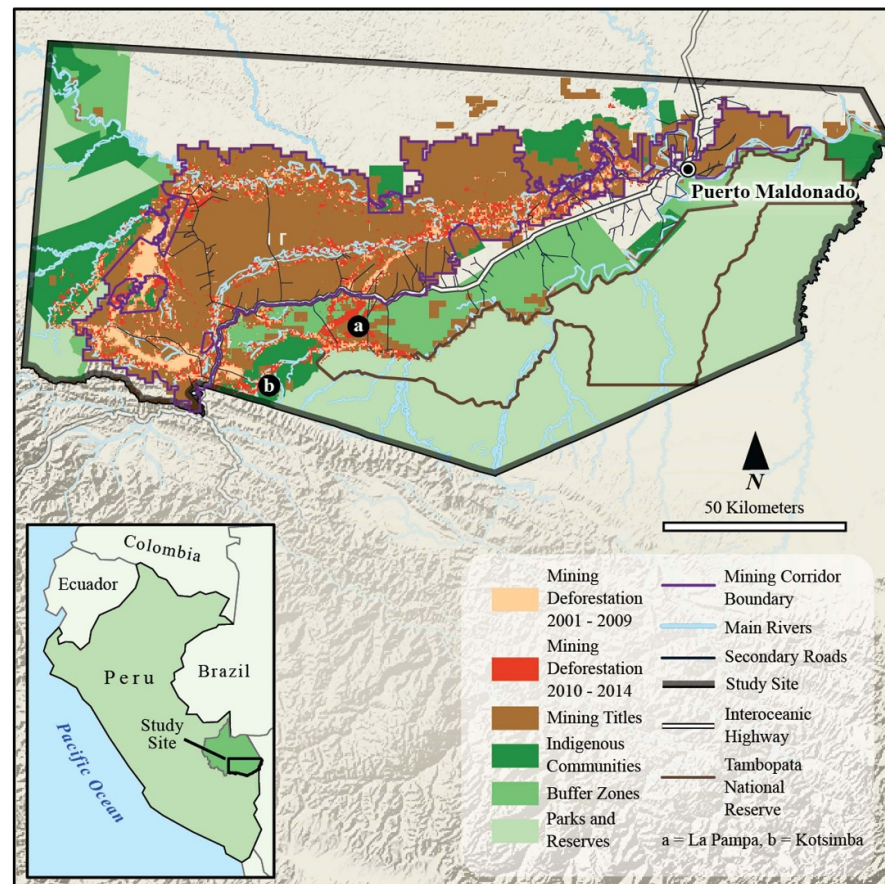


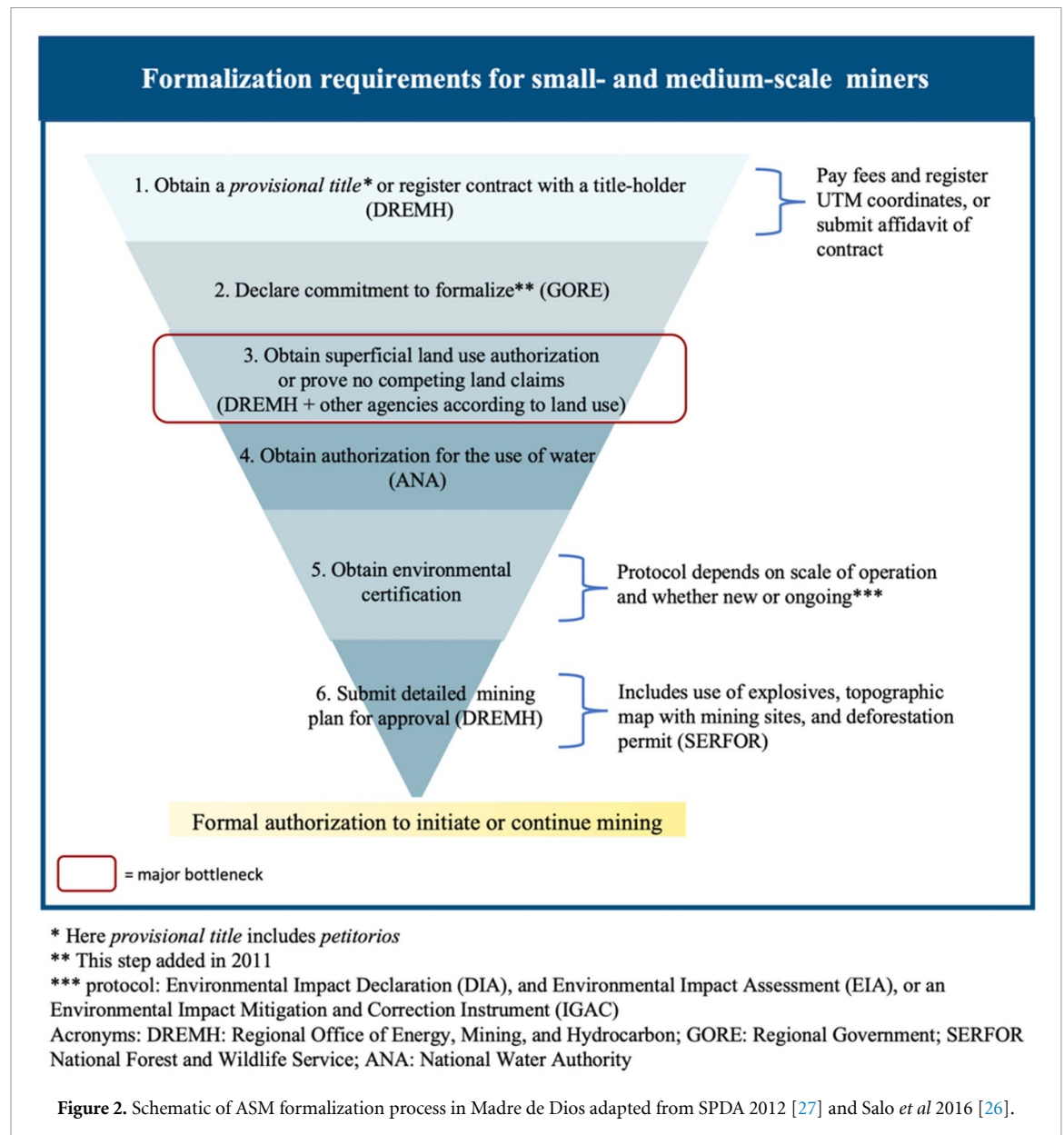
Figure 1. Map of study area, Madre de Dios, Peru highlighting the distribution of provisional mining titles, the mining corridor, and mining-related deforestation between 2001 and 2014. Graphic: K. McNair & T. Andersen/UW Cartography Lab.

granting concessions [29]. After 2008, illegal mining expanded quickly ($\sim 18\% \text{ yr}^{-1}$) as gold prices skyrocketed [30]. Simultaneously, the construction of the Interoceanic Highway (2006–2011) facilitated the influx of >30 000 migrants seeking gold and allowed heavy mining machinery to enter [31, 32] (table S1). By 2010, ASM had cleared >40 000 ha of forest [19]. Dangerous mercury levels were recorded in residents living downstream from mining [33]. In 2010, the government of President Alan García (2006–2011), responding to the outcry from international environmentalists, decreed gold mining in Mdd an issue of national concern (DU N° 012–2010) (table S1) [23]. This decree, which became permanent law in 2012, restricted all mining in Mdd to a 545 811 ha ‘corridor’, defined by the regional land use zoning exercise [34]. The corridor contained much of the area where titles had already been issued—titled miners therein were allowed to continue the formalization process but mining was no longer permitted outside the corridor⁶. Everything outside the corridor was

designated as a mining exclusion zone. The decree also prohibited all mining along and within waterbodies, such as palm wetlands, lakes, rivers, streams and their floodplains, including within the corridor.

The newly elected government of President Ollanta Humala promised to continue formalization efforts, approving the National Plan for the Formalization of Artisanal Mining (2011) that added further steps to the protocol for gaining a concession (table S1). By 2011, $\sim 17\,000 \text{ kg}$ of gold/year were extracted from Mdd, 99% classified as ‘ASM’ [30, 34]. The 2011 Plan formally codified a local norm, namely, that miners who had initiated the formalization process were considered *informal*, and those who did not were *illegal* (and targeted by police). By 2014, >5000 miners in Mdd initiated the formalization process, yet no individual was able to complete the process and earn the legal right to mine (figure 2) [26]. Mining conflicts grew more violent as national and local governments organized military and police interventions to stop illegal mining and destroy prohibited equipment [35]. Miners protested forcefully and their political power grew. All formalization paperwork stopped for four years beginning in 2014 when a mining leader was elected Governor of Mdd on an anti-regulatory platform [23]. In sum, at Mdd,

⁶ Technically, miners outside the corridor could continue *if* they had full legal rights (i.e. passed environmental impact assessments, proven no overlapping claims) but essentially no one had made it that far in the process.



as elsewhere, the formalization process has been incomplete and conflictive [5, 12, 26], and shaped by major economic and sociopolitical factors, including change in presidential administrations (see Timeline in table S1, and for deeper historical analysis, see [5, 23, 26, 36]).

2. Methods

We measure mining-related deforestation from 2001 to 2014, when >30 000 people came to mine gold and the government launched formalization programs [5]. Because of the global importance of Mdd's carbon-heavy and biodiverse forests, we focus on mining-related deforestation. We investigate: (a) whether issuing 1701 provisional individual titles was associated with a relative increase of mining in titled regulated areas, and (b) whether declaring a >5000 km² mining corridor confined mining to

one region and spared others. We use panel data on mining-related deforestation to examine how the timing, location, and extent of mining changed with the titling process and the declaration of the corridor, while controlling for major factors like gold price and distance to roads. Our quantitative analysis speaks most to the zoning aspect of formalization—to what degree has formalization influenced where mining happens? Interviews with miners and authorities elaborate further challenges associated with zoning, security and legibility.

2.1. Remote sensing

To map mining expansion, we classified annual Landsat imagery (table S2) and conducted post-classification map comparisons. Images were pre-processed to ensure comparability across sensors and enhanced using spectral indices that increased separability of mining areas [37] (figure S1). We

employed random forest (RF) tree-based classifiers (Vers. 4.6–14 [38, 39],) and individually trained classifiers to identify mining areas, forests, agricultural and herbaceous areas, water bodies, riverbanks, and other bare areas for each image year. We used high-resolution imagery and our on-site experience for classifier training and model accuracy assessment. The final RF models had out-of-bag errors yielding accuracy estimates from 0.94 to 0.99. Post-processing of the classified maps included masking clouds, alluvial banks, oxbow lakes, impervious surfaces, and areas of non-forests in the year 2000 [19, 30]. We also conducted manual adjustments to reclassify water ponds inside mining areas and remove image classification errors [40] (S1).

2.2. Modeling changes in mining associated with formalization

Our unit of analysis was a 25 ha hexagonal cell (figure S1). Descriptive statistics were calculated across the 20 850 km² study area (figure 1), which encompasses the majority of deforestation from mining activities [19, 40]. To limit our impact analysis to areas where gold-mining could reasonably have occurred, we use a restricted sample selected through a nearest-neighbor matching procedure, with hexagons inside the corridor matched to hexagons outside the corridor within the same district and geology and with similar distance to navigable rivers [41, 42] (S1). Data sources for all variables are summarized in table S2.

Our outcome variable—mining related deforestation—was calculated from the area attributed to the mining class⁷ in each hexagon in each year⁸. Because of the patchy distribution of mining, we performed analyses with two versions of the mining outcome variable: (a) a binary indicating presence of any mining in hexagon i during year j , and (b) the log-transformed area of mining within hexagon i in year j , only for instances where mining occurs. Thus, we model both the distribution of mining sites across the region (probability of mining) and the extent of clearing in established sites (intensity of mining). We also calculate the inverse hyperbolic sine of mined area for comparison (tables S5 and S6). We used linear probability models⁹ for binary outcomes and semi-elasticity models for area. Standard errors were clustered (5 km² resolution) to mitigate spatial autocorrelation.

⁷ We excluded instances with <3 pixels (0.27 ha) of mining to remove spurious bare areas caused by riverbank shifts, or single fields cleared for crops. Our models are robust to variations on this threshold.

⁸ For years 2002 and 2012 when no good images were available due to cloud cover and sensor malfunction, we interpolated values based on the midpoint of surrounding years.

⁹ We used linear probability models because logit-style models would exclude 80% of the legitimate observations, where there was never mining [57], and because of their greater clarity in interpretation of interaction terms [58].

2.2.1. Title-focused models

Mining Outcome_{ij} = $\beta_1 \times \text{titled}_{ij} + [\beta_{2-14} \times \text{year-indicator}_j \times \text{titled}_{ij}] + \delta \times \text{year-indicator}_j + \gamma \times \text{cell-indicator}_i$

Here, the main predictor variable of interest, ‘titled’, indicates whether the centroid of a hexagon had entered the titling process by a given year (figure S2). We modeled the overall effect for the whole study period and then included year–title interaction terms to allow the effect of title to differ over time. We controlled for time-invariant characteristics of each cell (e.g. geology, remoteness) with cell-level fixed effects (γ), and space-invariant characteristics of each year (e.g. price of gold) with year-level fixed effects (δ). We include an event study framework as a robustness check (figure S3).

2.2.2. Corridor-focused models

Mining Outcome_{ij} = $\beta_1 \times \text{Post-decree}_j + \beta_2 \times \text{Outside corridor}_i \times \text{Post-decree}_j + [\text{additional interactions with other zones}] + \delta \times \text{year-indicator}_j + \gamma \times \text{cell-indicator}_i$

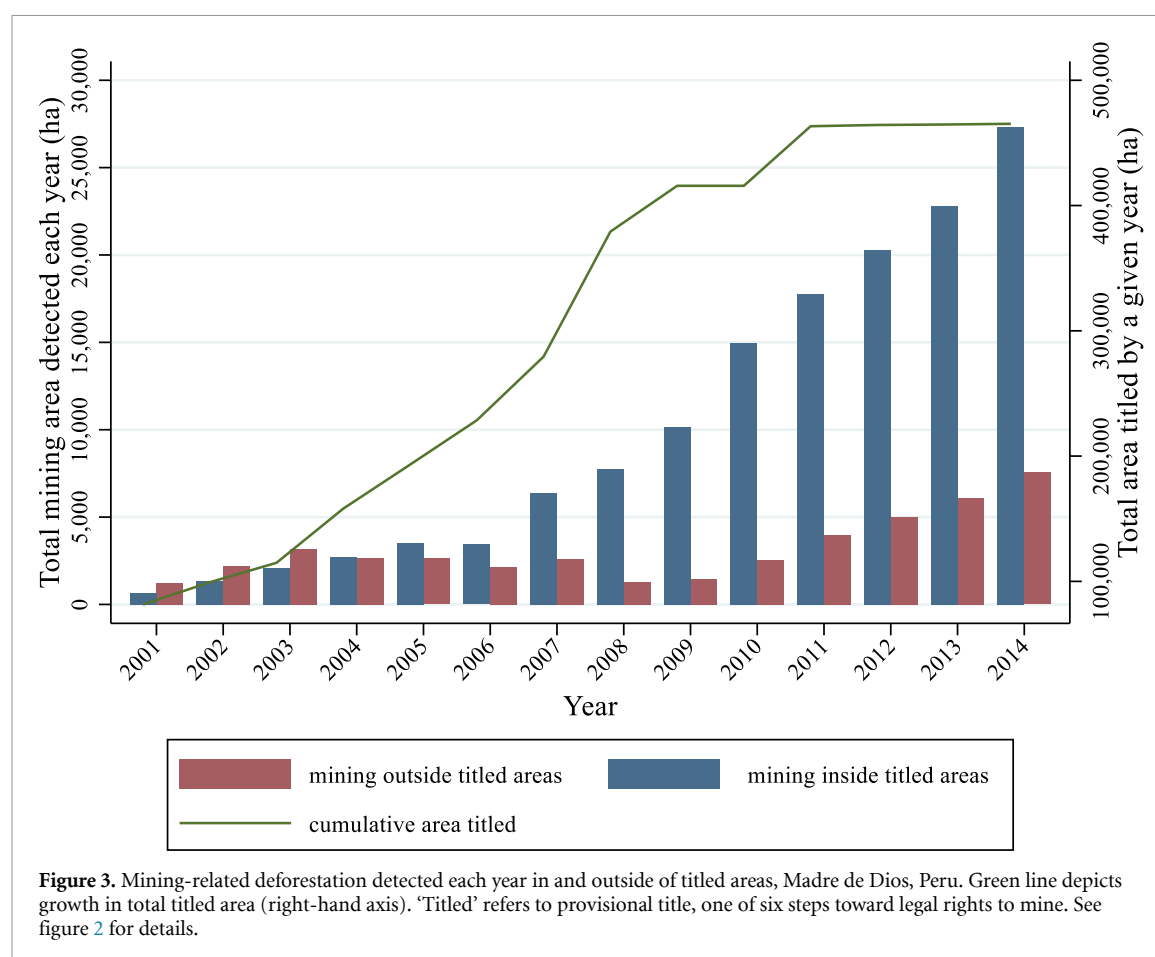
In the corridor analysis we employ a similar panel model structure with fixed effects for each cell and year. The main predictor of interest is an interaction indicating location outside the region that would become the corridor after it was declared in 2010, where mining was no longer permitted¹⁰. As a robustness check, we also examine a version of the model with separate corridor interactions for each year. We assess the mining change outside the corridor as a whole, and then allow separate interactions for other designations overlapping with the region outside the corridor: protected areas, buffer zones, indigenous communities, and areas within 0.5 km of rivers.

Our models use before-and-after comparisons of interventions (BACI), without randomization. This is the best option available since formalization interventions were not rolled out in a randomized way, though it does not provide as strong inference as randomized BACI [43, 44]. We supplement the quantitative analyses with qualitative information from interviews to contextualize interpretations of our time-series analyses.

2.3. Interviews

We spoke with 47 key informants in MdD and Lima in 2013, 2014, and 2020 (table S3). NAB also spent five days at a small-scale mine where she convened two focus groups. Interviews were semi-structured with questions on: (a) the respondent’s experience with formalization, (b) their perception of zoning effectiveness, and (c) their ideas on the cause and pattern of mining expansion during our study.

¹⁰ The main effects of the corridor location or locations of other time-constant zones like protected areas are absorbed into the cell-level fixed effects. The interaction gives the change in the effect of the associated zone over time.



3. Results

Our analysis revealed ~38 400 ha of mining-related deforestation between 2001 and 2014 (table S4). The total mining area was relatively stable through 2006 but increased rapidly afterward, especially inside titled areas (figure 3). The amount of land titled also increased, expanding fastest between 2003 and 2008 (figure 3). In all, 1701 titles were issued during our study, with a median size of 400 ha (range 100–1000 ha).

3.1. Mining deforestation and provisional titles

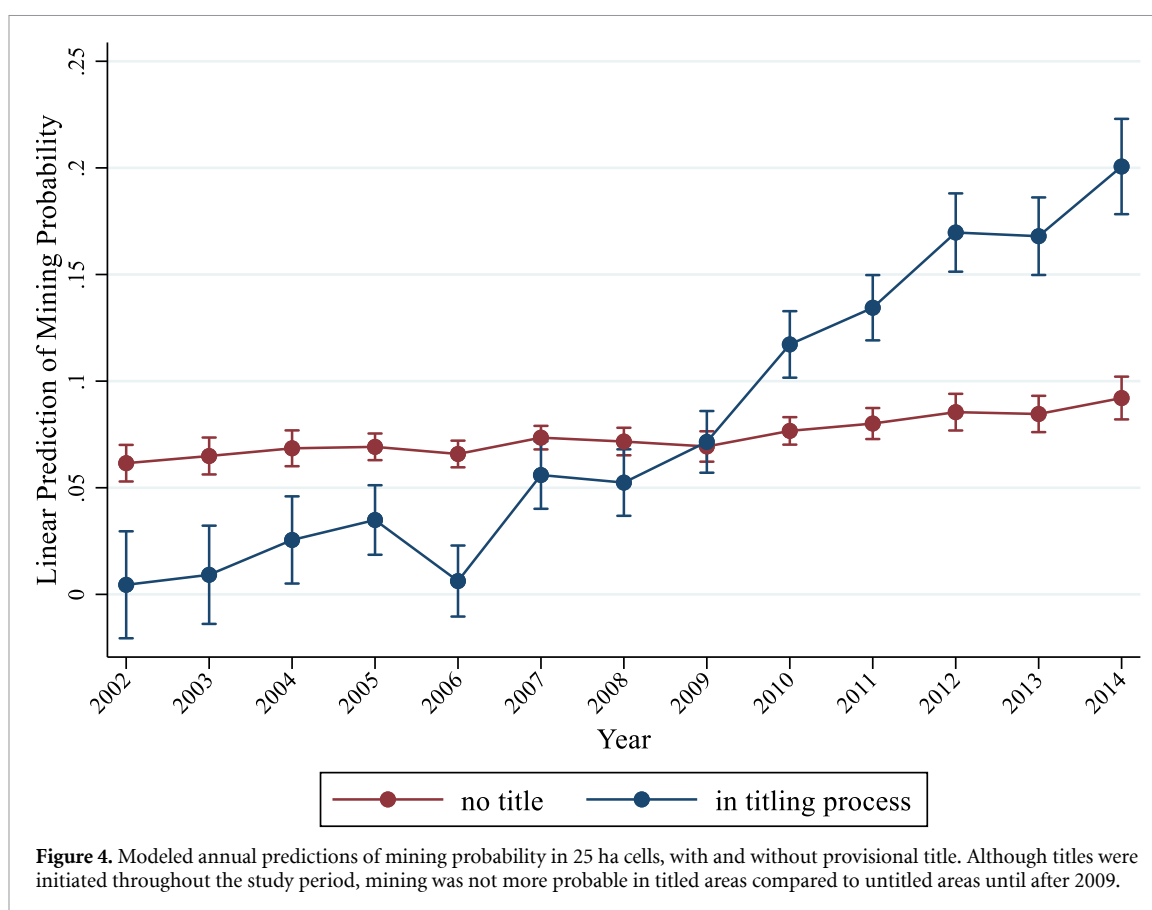
Overall, the probability of mining in a given site increased from about 7.5% in cells without title to 10.1% after the titling process was initiated, and this difference is statistically significant (table S5). However, the relationship between mining and titling varied considerably during our study, shifting from titles being associated with lower probabilities of mining-related deforestation in the early 2000s, to higher probabilities in titled areas after ~2009 (figure 4). The probability of mining rose in the years following the initiation of title relative to a baseline of 5 years beforehand, but mining was also significantly elevated as early as two years before the titling process was initiated (figure S3). The size of mining clearings did

not change significantly in relation to the titling process (table S5).

3.2. Mining deforestation and the corridor

When the 545 811 ha corridor was established, much of the area was already titled (67%–82%¹¹ (table S4)). After its declaration in 2010, mining was no longer permitted outside the corridor, and the probability of mining there did decrease significantly (by about six percentage points) relative to the probability inside the corridor (figure 5, table 1—Model 1A). However, mining area detected outside the corridor expanded by ~10 000 ha after 2010, and much of this was concentrated in a few sites (e.g. La Pampa, Kotsimba) (figure 1, table S4). Because of these sites, the proportion of annual mined area that occurred outside the corridor grew larger, from ~22% to >35%, even though the probability of mining occurring in any given place grew more slowly outside the corridor after its declaration (figure 5, table S4). When the corridor was declared, mining outside of it became more concentrated into a few specific areas.

¹¹ Calculated area depends on whether extinguished titles are included. Titles are extinguished if claimants did not pay fees. We did not include extinguished titles in our title effect analyses because of lack of data to distinguish when they were active vs. extinguished (table S4).



In protected area buffer zones and territories of native communities¹², mining probability rose and clearing sizes expanded by >40%, while elsewhere outside the corridor, mining probability fell and clearing sizes decreased by 27% (table 1—Model 2B). After 2010, mining probability also significantly increased (by about four percentage points) on land within 0.5 km of navigable rivers, contrary to zoning intentions (table 1—Model 1B).

3.3. Interviews

Our respondents (table S3) pointed to four reasons formalization did not mitigate the environmental damage of ASM: (a) provisional titling functionally granted rights to operate without responsibilities to meet environmental criteria, (b) some miners used titles to displace others and access credit to buy more powerful equipment, (c) the people actually mining in an area were often not titleholders, and (d) enforcement was erratic and difficult, partly because Andean derived regulations were a bad match for the Amazonian ecosystems.

No individual attained full legal rights to mine during our study (table S1). Agency and NGO staff criticized individuals for mining with only provisional titles.

People here (MdD) are wrong-headed, we give them a provisional title and they start to work. This is bad. Miners can't work until the environmental study is approved. [RESP#1]

In turn, miners complained that the process was overly burdensome, if not impossible.

It's all a lie. The government's Supreme Decree (2010) is not about formalization, it's about making mining disappear. (RESP#2)

Miners who initiated the titling process waited months for paperwork, although allegedly, those paying bribes were titled faster. Given delays and fees (RESP#3, table S7), miners felt they deserved to begin extracting gold. In fact, a mining official (RESP#4) confided that this was to be expected.

Several respondents reported that titles allowed miners to obtain loans for expensive mining equipment (table S7). No respondent mentioned miners using loans to buy cleaner technology, such as shaker tables, a mercury-free means of separating gold. After militaristic interdictions ramped up in ~2011, individuals increasingly sought formalization to be deemed 'in the process of formalization' or simply 'informal' (vs. 'illegal') (Legislative Decree 1105) and thus avoid police action including equipment destruction. In essence, allowing those with only

¹² There are no protected areas or indigenous communities inside the corridor, but the corridor does partially overlap with two buffer zones (BZ RN Tambopata, BZ RC Amarakaeri).

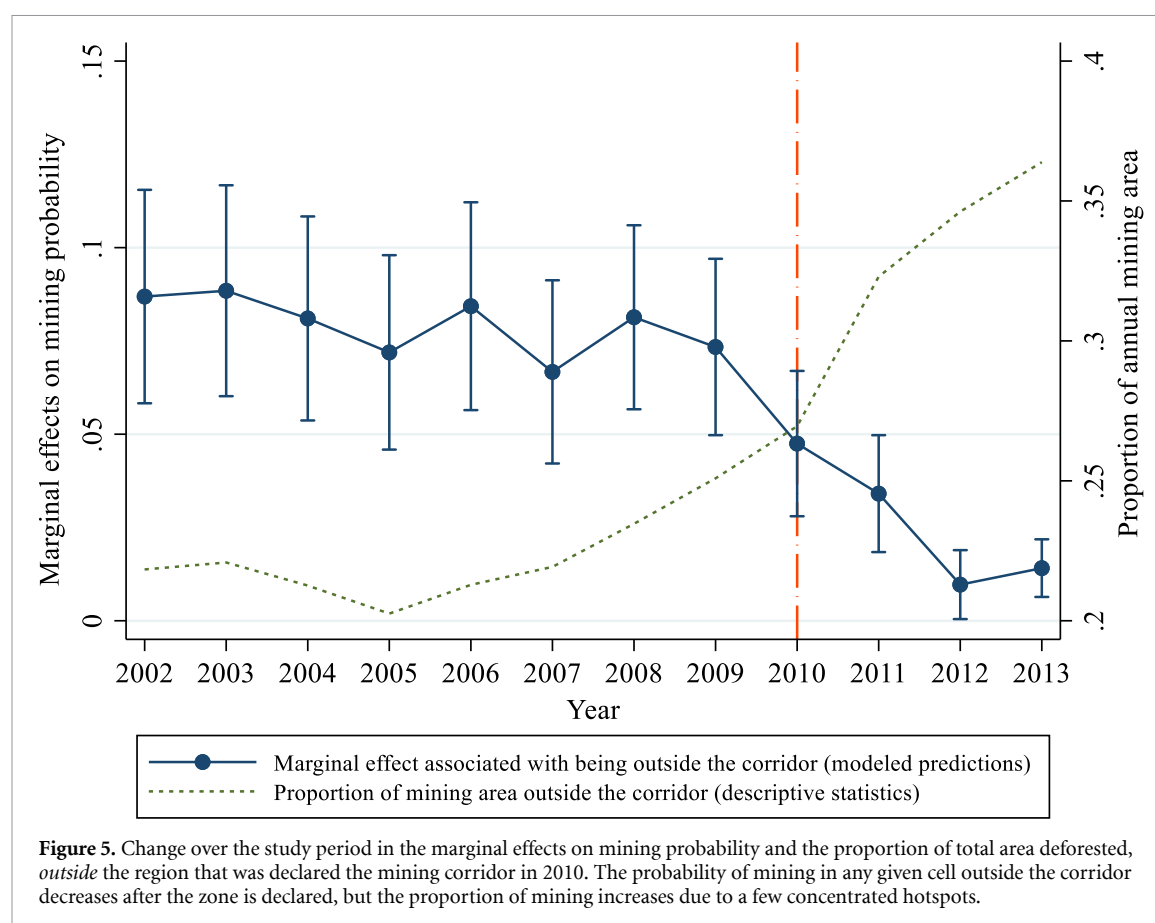


Table 1. Model results for mining changes after 2010 declaration of corridor.

	(1) Change in probability mining occurs in a cell		(2) Percent change in clearing size if mining occurs	
	A	B	A	B
Post-2010 x outside corridor	−0.06***	−0.08***	0.11	−0.27*
Post-2010 x in a protected area		0.00		0.32
Post-2010 x in a buffer zone		0.03†		0.46***
Post-2010 x in a native community		0.07***		0.42***
Post-2010 x within 0.5 km of nav. river		0.04***		−0.05
Post-2010	0.14***	0.13***	0.82***	0.73***
Constant	0.00	0.01	0.00	0.08
Effects for each year	Yes	Yes	Yes	Yes
Cell fixed effects	Yes	Yes	Yes	Yes
Num obs	520 128	520 128	40 800	40 800
Num panels	37 152	37 152	6185	6185

Significance thresholds indicated with following symbols: †: $p < 0.1$, *: $p < 0.05$, ***: $p < 0.001$

Inclusion of cell fixed effects absorbs main effects of stationary variables (like zones), so these are not separately reported.

M1 is a linear probability model, M2 is a semi-elasticity model of $\ln(\text{Area Cleared})$, conditional on mining occurring.

provisional titles to mine represents a compromise between environmental and mining interests. It also shows the political might of the mining sector.

Being the holder of (a provisional title)—is like an affidavit—you can mine while completing your environmental compliance. (Informal) miners were given a special allowance so as not to paralyze all mining in MdD given

that no one has all the requirements in force. (RESP#5).

Another motivation for entering the titling process was to secure claims vis-à-vis other miners and other land users especially as improved road access and rising prices precipitated a gold rush. Provisional titles were issued largely without regard for overlapping claims—miners are technically obliged to resolve these conflicts before they start

mining, but titles empowered some miners in land disputes.

Mining and Agriculture agencies have each managed their own cadaster. They (DREMH) never verify coordinates but just give permission to the miner no matter the surface claim. Having a (title) gives the miner a bit of power. (He says) 'I have in hand the permit. You only own the surface.' Some (farmers) can negotiate but the miner has more money (...) the farmer has to give way (RESP#6).

In addition to potential direct profits from gold, land rents are also in play. Many individuals with titles earn money by charging 'guest' (*invitados*) miners 'royalties' (*regalías*) for access. According to respondents, guest miners are commonplace, including within indigenous reserves, and are unconcerned with regulations (RESP#6; table S7).

In the Mining corridor there are 1900 (provisional title holders) and 5000 miners have declared commitment to formalize, but the rest, where are they? There are >30 000 miners in MdD. (RESP#7)

My dad's friend has 40 (provisional) titles but doesn't even own a motor. He lives off the royalties of guest miners. (RESP#6).

Guest miners are the biggest forest destroyers. They say 'if I'm paying you [the title holder] you can't demand I deal with the state'. They (guests) don't care if the title owner has the right to use mercury or cut forest. They don't care about water. And these guests invite others w/o permission of title holder. (RESP#8)

Speaking to mining's expansion outside the corridor, respondents described certain places, like La Pampa (figure 1, table S7), as beyond the law. They also told us that when designated, the corridor was already near-full of mining and that 'the mafia' controlled particularly gold-rich sites. Most respondents believed significant gold deposits lay outside the corridor. Furthermore, respondents agreed that enforcement was subject to ambiguity and political manipulation.

Every time there's an interdiction, miners get tipped off and hide their motors (and resume work after). Miners in La Pampa (figure 1) contributed to the president's campaign so there was no enforcement there (RESP#9).

The Minister of the Environment (under Pres. García) put a tough hand on illegal miners. The miners reacted to the military pressure by withdrawing (from illegal sites). But there was a change of government and the new government backed off (reduced the military pressure). Then the miners came back even stronger (RESP#10).

Some also explained that within the corridor and beyond, the waterway rules were hard to interpret given the serpentine, ever-changing courses of streams.

There is no map of exclusion zones (waterways and wetlands) within the corridor. Here mining is prioritized and enforcement is absent. It is presumed that all types of mining are permitted in the corridor (RESP#11).

4. Discussion

Our work yields lessons about the tenuous connection between formalization and improved environmental outcomes in ASM.

4.1. Zoning

Our spatial analysis shows that formalization was associated with changes in mining deforestation patterns, but not always as intended. In the early 2000s, there was actually less mining in titled areas compared to elsewhere. As gold prices rose, the corridor was declared in 2010, and enforcement increased (table S1), the probability of new mining became higher in titled areas and inside the corridor. Although this shift was as hoped, there are several caveats to interpreting it as a land-sparing effect. First, the proportion of mining-related deforestation across the study area increased outside the corridor due to the expansion of a few major mining sites in protected area buffer zones and certain indigenous communities (figure 1). The scatter-shot mining more commonly associated with smaller scale independent actors may have been curbed, but controlling mining at gold-rich accessible sites with more capitalized actors proved extremely difficult. Second, from our results, it is not clear whether the corridor 'soaked up' new mining that would have started elsewhere, or prompted miners already present to open new areas because they worried less about government interdictions. This ambiguity is important because improved access and high gold prices continue to bring more miners to MdD. Finally, we see suggestions that formalization often follows the miners rather than prescribing where mining should occur, as when titles are sought for areas where mining has already begun or when the corridor is declared atop of a region that is mostly already titled.

More broadly, our work cautions against assumptions underlying land-sparing ideas, namely presupposing there are ‘open’ spaces to devote to ASM. Even in remote parts of MdD, overlapping and contested claims are commonplace and the legal capacity to resolve land conflicts is limited. Recommendations to create ASM zones and ‘confine it’ [2] sound reasonable, but our work and others [13, 39, 45] show this is difficult as gold prices soar and access improves, especially if alluvial deposits are scattered over the landscape. Limiting roads (and thus heavy machinery) into gold-rich intact forests may be more important than declaring ASM zones [36]. The regulators and miners we interviewed agreed that it is difficult to apply and enforce regulations derived from hard-rock mining in the Andes to Amazonian ecosystems. For example, prohibitions about mining near waterways are hard to enforce when river courses regularly shift and the water table lies near the surface. Ultimately, the extent to which zoning can confine mining depends largely on enforcement [13], which during our study was inconsistently applied at MdD due to physical challenges, political shifts and alleged corruption [46].

4.2. Security

A prominent global report predicts that providing miners legal rights, technical support and bank loans will improve social and environmental outcomes [2]. We found no evidence that granting titles gave miners a sense of security that encouraged better adherence with environmental regulations. Our respondents explained that provisional titles actually came to function as a ‘de facto’ permit to mine *without* mitigating environmental damage or reconciling competing land claims, an outcome also documented in Colombia [47]. Some miners even used provisional titles to intimidate and displace farmers or forest stewards, as elsewhere [14] but see [48]. Others profited from speculating in titles. In the Philippines, high gold prices also made the permitting process more difficult and conflictive [45]. Although most miners at MdD want more secure working conditions [5, 26], the issuance of provisional titles did not slow the ‘rush’ mindset. Thus we caution against assuming that because more secure ownership tends to favor forests in the context of smallscale agriculture [8], the relationship will hold for alluvial mining, a non-regenerative activity. That said, we did not study mercury use, a key concern. Formalization purportedly reduced mercury contamination at a Colombian site, but it is not clear how [16]. In MdD some newly titled miners did obtain loans for new machinery, but this was to accelerate mining (table S7), not to avoid mercury use. An analysis of mercury use and abatement technology is beyond the scope of our paper, but Peru’s recent commitment to comply

with the Minamata Accord on Mercury Use is promising [49].

4.3. Legibility

The prevalence of ‘guest’ miners in MdD highlights a challenge to the hope that formalization would increase the visibility and accountability of miners. Instead, a rent market has developed with commercial patronage agreements between title holders and temporary miners (some highly capitalized) who were even farther removed from regulatory reach. Provisional titles allowed the government to extract rents from the claimants and allowed title holders to extract rents from guests, but the redistribution of profits did not necessarily improve environmental outcomes. Similar complex and highly unequal arrangements have been reported elsewhere [11, 45]. Legibility and accountability issues are even more complex in indigenous territories. In the worst case, formalization campaigns help outsiders mine gold against the communities’ interest [50]. However, indigenous leaders also reported more consensual and profitable arrangements in some territories. The complexity and heterogeneity of guest mining and patronage arrangements make it difficult to discern between invasion and invitation.

When it comes to legibility, too often formalization models paint a simple picture of the state imposing its regulations on passive miners. The MdD case shows that informal miners may collectively have considerable political power. Contrary to examples of local citizens risking their lives to fight corporate mines in the Andes [24], in MdD local citizens protested restrictions on mining and some lost their lives doing so (table S1). On the other hand, a stalwart local management committee in one part of MdD (Tambopata) has called out the worst polluters and worked to forge new models for managing mining [51]. Last, in MdD as in the Andes, adherence to regulations may be weakened by divisions within the government about prioritizing mining or the environment [24]. This power struggle partly explains why formalization rules were ‘bent’ to accommodate miners. Here, as is often the case, there is no clean boundary between, nor consistency within state and local agendas.

4.4. Looking forward

Remote sensing is a powerful tool for mapping the loss of biodiverse, carbon-heavy forests to ASM, and our measurements match a similar study at MdD [19]. However, our approach has limitations, including those associated with the challenges of detecting illicit activities leading to land degradation [52]. We were unable to test effectiveness of rules against mining along waterways because we could not reliably discern mining on riverbanks from natural erosional processes, particularly for small operations typical of illegal mining [30]. In fact, we generally miss very

small clearings by excluding potentially spurious bare patches, thus our estimates of mining area represent a lower bound. Also, our remote sensing-based analysis did not allow us to measure the effect of formalization on mercury, an urgent problem. It will also be important to evaluate formalization efforts in which full rather than provisional titles are achieved, though ASM formalization is seldom fully implemented in remote tropical regions [13] often because of the same obstacles documented at MdD (e.g. contradictory land rights, weak agencies) [5, 12, 18, 26]. Finally, our ability to draw causal inference is limited because formalization did not occur in a randomized way. Titling and zoning unfolded concurrent with changes in political administration, enforcement pressure, and conservation interventions [5, 23].

Attempts to govern ASM in MdD continued to unfold after the hiatus in formalization interventions from 2014 to 2018. A major enforcement effort (Operation Mercury) was launched in 2019 and deforestation in the Tambopata Buffer zone slowed substantially for a period [53]. Formalization efforts began anew in MdD in 2019 and 243 miners (out of thousands) completed the entire process and acquired legal concessions [54]. Since then, gold prices have remained high during the COVID-19 pandemic and there are reports of miners taking advantage of the government's diverted attention [55].

4.5. Conclusion

Our findings offer precautionary lessons about the ability of formalization to deliver environmental benefits. Ultimately, alluvial mining is largely incompatible with conserving tropical forests. Perhaps for this reason, and because of the millions of poor people involved, articles on how to reform ASM formalization focus on measures to improve equity and protect workers but say little about how such measures will protect forests or wetlands. Our findings suggest that formalization may have a concentrating effect on mining, but certain issues can attenuate environmental benefits. Some are familiar—e.g. enforcement is necessary and corruption is likely. We also raise less familiar concerns. ASM in the fluid and shifting Amazon ecosystem is much more difficult to spatially delineate than hard-rock mining in upland regions. The vision of 'settled' miners stewarding their concessions over the long term is far afield from MdD conditions. Title holders are not necessarily the miners, and mining in titled areas does not signify compliance with environmental regulations. Finally, clarity in land rights is an unmet precondition for a functional titling process, and there is seldom 'open land' for mining. For formalization to work as intended, the rules and process will need to be crafted in a way that attends to regional context and (conflicting) local and national agendas [48]. This accords with calls for innovation in mining institutions, ideally before extraction begins [24]. The explosive growth in ASM

(sixfold increase in the global number of artisanal miners over 5 years) makes this difficult and urgent [56]. Against this challenge, we join others in calling for more explicit and context-specific attention to the mechanisms by which formalization will improve environmental outcomes.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

N A-B, J L'R, and L N-T designed research; N A-B conducted remote sensing analysis; N A-B conducted focus groups; N A-B and L N-T conducted and analyzed interviews; N A-B obtained data layers and prepared layers for analysis; J L'R designed and performed quantitative analysis; N A-B, J L'R and L N-T wrote the paper.

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References

- [1] Álvarez-Berrios N L and Mitchell Aide T 2015 Global demand for gold is another threat for tropical forests *Environ. Res. Lett.* **10** 014006
- [2] Fritz M M C, McQuilken J, Collins N and Weldegioris F 2017 Global trends in artisanal and small-scale mining (ASM): a review of key numbers and issues [Research Report] (Manitoba: International Institute for Sustainable Development) hal-02547257
- [3] Holland L 2020 Illegal gold mining and the struggle to save the Amazon in Peru *Frontiers of Development in the Amazon:*

- Riches, Risks, and Resistances* ed A A R Ioris, R R Ioris and S Shubin (Washington, DC: Rowman & Littlefield)
- [4] Csillik O and Asner G P 2020 Aboveground carbon emissions from gold mining in the Peruvian Amazon *Environ. Res. Lett.* **15** 14006
 - [5] Damonte G H 2016 The 'Blind' state: government quest for formalization and conflict with small-scale miners in the Peruvian Amazon *Antipode* **48** 956–76
 - [6] Román-Dañobeytia F, Huayllani M, Michi A, Ibarra F, Loayza-Muro R, Vázquez T, Rodríguez L and García M 2015 Reforestation with four native tree species after abandoned gold mining in the Peruvian Amazon *Ecol. Eng.* **85** 39–46
 - [7] Siegel S and Veiga M M 2009 Artisanal and small-scale mining as an extralegal economy: de Soto and the redefinition of 'formalization.' *Resour. Policy* **34** 51–56
 - [8] Robinson B E, Holland M B and Naughton-Treves L 2014 Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation *Glob. Environ. Change* **29** 281–93
 - [9] Scott J C 2020 *Seeing like a State: How Certain Schemes to Improve the Human Condition Have Failed* (New Haven, CT: Yale University Press)
 - [10] Putzel L, Kelly A B, Cerutti P O and Artati Y 2015 Formalization as development in land and natural resource policy *Soc. Nat. Resour.* **28** 453–72
 - [11] Maconachie R and Hilson G 2011 Safeguarding livelihoods or exacerbating poverty? Artisanal mining and formalization in West Africa *Nat. Resour. Forum* **35** 293–303
 - [12] Geenen S 2012 A dangerous bet: the challenges of formalizing artisanal mining in the Democratic Republic of Congo *Resour. Policy* **37** 322–30
 - [13] Marshall B G and Veiga M M 2017 Formalization of artisanal miners: stop the train, we need to get off! *Extr. Ind. Soc.* **4** 300–3
 - [14] Jonkman J 2019 A different kind of formal: bottom-up state-making in small-scale gold mining regions in Chocó, Colombia *Extr. Ind. Soc.* **6** 1184–94
 - [15] Peluso N L 2018 Entangled territories in small-scale gold mining frontiers: labor practices, property, and secrets in Indonesian gold country *World Dev.* **101** 400–16
 - [16] Haeni J 2020 Tackling threats from illegal mining (10 April 2020) (<https://medium.com/usaaid-2030/tackling-threats-from-illegal-mining-8ad935290b7>)
 - [17] Rettberg A and Ortiz-Riomalo J F 2016 Golden opportunity, or a new twist on the resource–conflict relationship: links between the drug trade and illegal gold mining in Colombia *World Dev.* **84** 82–96
 - [18] USAID 2020 Artisanal and small-scale mining: USAID activities and approaches p 27 (<https://land-links.org/wp-content/uploads/2020/01/USAID-ASM-Issue-Brief-Jan-2020.pdf>)
 - [19] Asner G P and Tupayachi R 2017 Accelerated losses of protected forests from gold mining in the Peruvian Amazon *Environ. Res. Lett.* **12** 94004
 - [20] Vanthomme H, Sánchez Cuervo A M, Gárate P, Dallmeier F and Bravo A 2019 *The Future of Madre De Dios: Smithsonian's Working Landscape Simulator for Sustainable Development* (Washington, DC: Smithsonian Scholarly Press) (<https://doi.org/10.5479/si.9781944466282.En>)
 - [21] Ceballos G and Ehrlich P R 2006 Global mammal distributions, biodiversity hotspots, and conservation *Proc. Natl Acad. Sci.* **103** 19374–9
 - [22] Asner G P, Martin R E, Knapp D E, Tupayachi R, Anderson C B, Sinca F, Vaughn N R and Llactayo W 2017 Airborne laser-guided imaging spectroscopy to map forest trait diversity and guide conservation *Science* **355** 385–9
 - [23] Cortés-McPherson D 2019 Expansion of small-scale gold mining in Madre de Dios: 'capital interests' and the emergence of a new elite of entrepreneurs in the Peruvian Amazon *Extr. Ind. Soc.* **6** 382–9
 - [24] Bebbington A J and Bury J T 2009 Institutional challenges for mining and sustainability in Peru *Proc. Natl Acad. Sci.* **106** 17296–301
 - [25] Ipenza Peralta C A 2012 *Manual Para Entender: La Pequeña Minería Y La Minería Artesanal Y Los Decretos Legislativos Vinculados a La Minería Ilegal* (Lima: Sociedad Peruana de Derecho Ambiental) (<https://spda.org.pe/wpfb-file/manual-de-mineria-3ra-edicion-pdf/>)
 - [26] Salo M et al 2016 Local perspectives on the formalization of artisanal and small-scale mining in the Madre de Dios gold fields, Peru *Extr. Ind. Soc.* **3** 1058–66
 - [27] SPDA 2012 El camino de la formalización del pequeño minero y el minero artesanal 1 (https://spda.org.pe/wpfb-file/20120919123018_camino-minero-pdf/)
 - [28] Gustafsson M-T and Scurrah M 2019 Strengthening subnational institutions for sustainable development in resource-rich states: decentralized land-use planning in Peru *World Dev.* **119** 133–44
 - [29] GOREMAD 2011 Plan de formalización y reconversión de la minería en Madre de Dios (Puerto Maldonado: Gobierno Regional de Madre de Dios, Comisión Especial - RER No. 103-2011-GOREMAD/PR) p 65 (https://nanopdf.com/download/plan-de-formalizacion-y-reconversion_pdf)
 - [30] Swenson J J, Carter C E, Domec J-C and Delgado C I 2011 Gold mining in the Peruvian Amazon: global prices, deforestation, and mercury imports *PLoS One* **6** e18875
 - [31] Goldstein R E 2015 The Triangular Traffic in Women, Plants, and Gold: Along the Interoceanic Road in Brazil, Peru, and Bolivia (Berkeley, CA: University of California) (https://digitalassets.lib.berkeley.edu/etd/ucb/text/Goldstein_berkeley_0028E_15377.pdf)
 - [32] Dammert-B. J 2018 Financing infrastructure projects in the southern Amazon of Peru: its relation with environmental and social safeguards (https://www.bu.edu/gdp/files/2018/10/GEGL_GDP-Peru-WP.pdf)
 - [33] Diringer S E, Feingold B J, Ortiz E J, Gallis J A, Araújo-Flores J M, Berky A, Pan W K Y and Hsu-Kim H 2015 River transport of mercury from artisanal and small-scale gold mining and risks for dietary mercury exposure in Madre de Dios, Peru *Environ. Sci. Processes Impacts* **17** 478–87
 - [34] Álvarez J, Brack V and Ipenza C 2011 *Minería Aurífera En Madre De Dios Y Contaminación Con Mercurio, Una Bomba De Tiempo* (Lima: Ministerio del Ambiente) (<https://repositoriodigital.minam.gob.pe/handle/123456789/229>)
 - [35] Weisse M J and Naughton-Treves L C 2016 Conservation beyond park boundaries: the impact of buffer zones on deforestation and mining concessions in the Peruvian Amazon *Environ. Manage.* **58** 297–311
 - [36] Caballero Espejo J, Messinger M, Román-Dañobeytia F, Ascorra C, Fernandez L and Silman M 2018 Deforestation and forest degradation due to gold mining in the Peruvian Amazon: a 34 year perspective *Remote Sens.* **10** 1903
 - [37] Townsend P A, Helmers D B, Kingdon C C, McNeil B E, de Beurs K M and Eshleman K N 2009 Changes in the extent of surface mining and reclamation in the Central Appalachians detected using a 1976–2006 Landsat time series *Remote Sens. Environ.* **113** 62–72
 - [38] Liaw A and Wiener M 2002 Classification and regression by random forest *R News* **2** 18–22 (https://www.r-project.org/doc/Rnews/Rnews_2002-3.pdf)
 - [39] Dezécache C, Faure E, Gond V, Salles J-M, Vieilledent G and Hérault B 2017 Gold-rush in a forested El Dorado: deforestation leakages and the need for regional cooperation *Environ. Res. Lett.* **12** 034013
 - [40] Scullion J J, Vogt K A, Sienkiewicz A, Gmur S J and Trujillo C 2014 Assessing the influence of land-cover change and conflicting land-use authorizations on ecosystem conversion on the forest frontier of Madre de Dios, Peru *Biol. Conserv.* **171** 247–58
 - [41] Jones K W and Lewis D J 2015 Estimating the counterfactual impact of conservation programs on land cover outcomes:

- the role of matching and panel regression techniques *PLoS One* **10** 1–22
- [42] Schleicher J, Eklund J, D. Barnes M, Geldmann J, Oldekop J A and Jones J P G 2020 Statistical matching for conservation science *Conserv. Biol.* **34** 538–49
- [43] Murtaugh P A 2002 On rejection rates of paired intervention analysis *Ecology* **83** 1752–61
- [44] Stewart-Oaten A 2003 On rejection rates of paired intervention analysis: comment *Ecology* **84** 2795–9
- [45] Verbrugge B and Besmanos B 2016 Formalizing artisanal and small-scale mining: whither the workforce? *Resour. Policy* **47** 134–41
- [46] Chávez A B 2013 Landscape dynamics of Amazonian deforestation between 1986 and 2007 in southeastern Peru: policy drivers and road implications *J. Land Use Sci.* **9** 1–24
- [47] Echavarría C 2014 ‘What is legal?’ Formalising artisanal and small-scale mining in Colombia IIED, London ARM, *Colomb* 79 (<http://www.responsiblemines.org/wp-content/uploads/2017/05/What-is-legal-C-Echavarría.pdf>)
- [48] Scullion J J, Vogt K A, Winkler-Schor S, Sienkiewicz A, Peña C and Hajek F 2016 Designing conservation-development policies for the forest frontier *Sustain. Sci.* **11** 295–306
- [49] Moody K H *et al* 2020 Mercury emissions from Peruvian gold shops: potential ramifications for Minamata compliance in artisanal and small-scale gold mining communities *Environ. Res.* **182** 109042
- [50] Rorato A C, Camara G, Escada M I S, Picoli M C A, Moreira T and Versteegen J A 2020 Brazilian amazon indigenous peoples threatened by mining bill *Environ. Res. Lett.* **15** 1–12
- [51] Orihuela J C 2017 Assembling participatory Tambopata: environmental entrepreneurs and the political economy of nature *For. Policy Econ.* **80** 52–62
- [52] Tellman B, Magliocca N R, Turner B L and Verburg P H 2020 Understanding the role of illicit transactions in land-change dynamics *Nat. Sustain.* **3** 175–81
- [53] Monitoring of the Andean Amazon Project 2019 MAAP #104: major reduction in illegal gold mining from Peru’s Operation Mercury (https://maaproject.org/2019/lapampa_opermercury/)
- [54] Dirección Regional de Energía Minas e Hidrocarburos (DREMH) 2020 Plan de formalización y reactivación económica de la minería en Madre de Dios en tiempos del COVID-19 (Puerto Maldonado: Gobierno Regional de Madre de Dios)
- [55] Dupraz-Dobias P 2020 High gold prices spur more illegal mining in Peru SWI (<https://www.swissinfo.ch/eng/gold-finds-favour-in-the-pandemic-but-at-what-cost-/45987080#:~:text=The%20boom%20in%20gold%20prices,imperiling%20lives%20and%20the%20environment>)
- [56] Stocklin-Weinberg R, Veiga M M and Marshall B G 2019 Training artisanal miners: a proposed framework with performance evaluation indicators *Sci. Total Environ.* **660** 1533–41
- [57] Beck N 2019 Estimating grouped data models with a binary-dependent variable and fixed effects via a logit versus a linear probability model: the impact of dropped units *Public Health Nutr.* **22** 139–45
- [58] Ai C and Norton E C 2003 Interaction terms in logit and probit models *Econ. Lett.* **80** 123–9