Commodity Price Shocks and Illicit Supply Chains

Evidence from the Gold Rush in the Peruvian Amazon*

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Abstract

This paper studies how informal and illegal supply chains of raw materials respond to global demand shocks, by exploring the case of the small-scale gold mining during the gold-rush in the Peruvian Amazon. For this purpose, this paper estimates the heterogeneous responses of small-scale gold mining to variations in the international price of gold. Using a combination of medium-resolution satellite images and official geographical information of mining sites, this paper provides evidence that differences in mining activity between illegal and non-illegal producers disappear in the wake of high prices. The results suggest that price booms induced a more than proportional proliferation of illegal mining activity in relation to non-illegal gold mining, which might be associated with a rise in the relative profitability of these producers. This might lead to a reconsideration of the current policy approach to limit the profitability of illegal gold producers in the area studied that underestimate the importance of price shocks.

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1 Introduction

Unintended consequences from participation in international trade can arise when sourcing economies are endowed with precarious institutional local conditions, poor labor markets, and informal or illegal production networks to supply global markets (Mehlum et al., 2006; Angrist and Kugler, 2008; Brückner and Ciccone, 2010; Van der Ploeg, 2011; Dube and Vargas, 2013; Berman et al., 2017; Saavedra and Romero, 2021). Given the nature of informal and illegal activities, data limitations implies that this dimension has been much less studied in the academic literature. In particular, because trade from illegal sources tends to be hidden through formal intermediaries, making difficult to trace and measure the extent of those activities and how they respond to foreign demand shocks.[1]

Within illicit trade, one of the most environmentally destructive and dangerous but highly profitable illegal activities in developing countries, is the illegal mining of precious minerals (SPDA, 2015; UNEP-INTERPOL, 2016; OECD, 2016; Berman et al., 2017). At 2015, it was estimated that trade in illegal mining was an industry that worth annually between 12 to 48 billion US$, equivalent to 1-4% of total mining industry trade (UNEP-INTERPOL, 2016; Global Financial Integrity, 2017).[2] As the profitability of these activities is directly linked to a surge in global demand (OECD, 2016), it is crucial to develop a better understanding of the extent to which price booms affect the expansion of these informal and illicit forms of extractive industries in relation to formal mining. As these are margins of response to foreign demand shocks that can have important consequences for economic development. Moreover, considering that the price of these commodities experienced a significant rise during the last two decades, and are expected to continue rising in the following years.

Within the industry of illegal mining of precious minerals, gold mining is the most profitable. This activity is highly concentrated in Latin America, and particularly in the Amazon region.[3] With an estimated annual worth of 7 billion US$ produced in the region at 2016. Equivalent to more than twice the annual total worth of global illicit trade of diamonds

[1]The measuring of these costs is nowadays a major concern for policy makers and scholars, specially when disruptions in global supply chains makes more difficult to enforce responsible sourcing.

[2]This is at least six times the annual worth of the illicit diamond trade that at 2015 worth around 2.74 billion US$ (Global Financial Integrity, 2017). And there is evidence that in the contexts of this activity has surpassed the profitability of coca production (SPDA, 2015). Despite the existing evidence studying how these activities foster conflicts (Berman et al., 2017), and its environmental consequences (Romero and Saavedra, 2019), there is a lack of evidence on how the illegal activity itself respond to global demand shocks in relation to alternative legal activities.

[3]This is in part explained because alluvial gold mining is less costly and more difficult to control in comparison to underground gold mining. Moreover given the remoteness of mining sites in the Amazon region (SPDA, 2015).

(Global Financial Integrity, 2017).[4] The industry has acquired worldwide notoriety due to its large visible environmental impacts caused by deforestation, and the precarious working conditions and negative consequences induced by the intensive use of mercury on production (Bebbington and Bury, 2009; Swenson et al., 2011; Ashe, 2012; Blackman et al., 2017; Romero and Saavedra, 2019; Tollefson, 2021).[5] It is estimated that illegal mining have contaminated over 30 rivers in the Amazon region, and just in Peru approximately 40 tonnes of mercury are dumped each day in the Amazon rivers due to artisanal and small-scale gold mining activity (SPDA, 2015).

During the past decade, governments have been investing enormous efforts to discourage illegal gold mining activity in the Amazon region in order to mitigate these negative effects, but with unsuccessful results (e.g., Saavedra and Romero, 2021).[6] A remarkable case within Latin America is the vast expansion of illegal gold mining in the Peruvian Amazon experienced during the last two decades. Peru is the largest illegal (and non-illegal) gold producer in Latin America. It is estimated that at 2016, Peru represented approximately 37% of the illegal gold produced in the region (Global Financial Integrity, 2017). Given its relevance, this paper explores the case of the Peruvian Amazon gold rush to shed light on the differences in mining activity between formal, informal, and illegal small-scale gold producers, and how these differences respond to shocks to the international price of gold.[7]

Consequently, the empirical strategy is divided in two parts. First, the differences in the intensity of mining activity between formal, informal, and illegal gold mining producers are explored. Then, in the second part, given the robust differences in mining activity found between illegal and non-illegal producers, the price elasticities and its heterogeneous effects distinguishing between these types of producers are reported. The evidence shows that the difference between formal and informal artisanal and small-scale gold mining is negligible and not statistically significant. Potentially explained by the diffuse institutional boundaries that distinguish these two groups. However, the difference in activity between illegal and non-illegal mining sites (considering both formal and informal sites), is large, statistically significant and robust. Suggesting a much more clear contrast between both types of producers that is further explored in the estimates.

Consistent with the existing empirical literature, the price elasticity in relation to the activity in mining sites is high, of about 0.5 to 0.8, and robust to the inclusion of various fixed

[4]Within the empirical literature, illegal mining of diamonds have received the most attention.

[5]Alluvial gold mining is a type of mining characteristics of the small-scale and artisanal gold producers in the Amazon region that uses water at high pressure to remove and then filtered the soil from gold particles.

[6]The difference between artisanal and small-scale producers is made in the literature to highlight that artisanal producers can be much less organized with highly precarious technology of production.

[7]Gold mining in the Amazon region is predominantly dominated by artisanal and small-scale mining given that the type of mining developed in the area, alluvial gold mining, is not profitable at a large scale.

effects and controls. Naturally, this is indicative of an important dependence of activity in artisanal and small-scale gold mines to variations in the international price of gold. But more importantly, the interaction between the price of gold and the type of mine (illegal vs non-illegal), reveals an important gap associated with the price effect between these producers that disappears for high values of the price of gold. In other words, the evidence suggest that a price boom particularly large can lead to a more than proportional increase in the intensity of illegal gold mining activity in relation to non-illegal mining, potentially explained by a rise in the relative profitability of illegal versus non-illegal gold mining activity. These results shows the relevance of the price shock for the proliferation and intensity of illegal mining activity that might redirect future policy intervention.

The rest of the paper is organized as follows. The context of the empirical case studied is commented in section 2. Section 3 presents the data and methodology. Followed by results and conclusions in sections 4 and 5 respectively.

2 Background

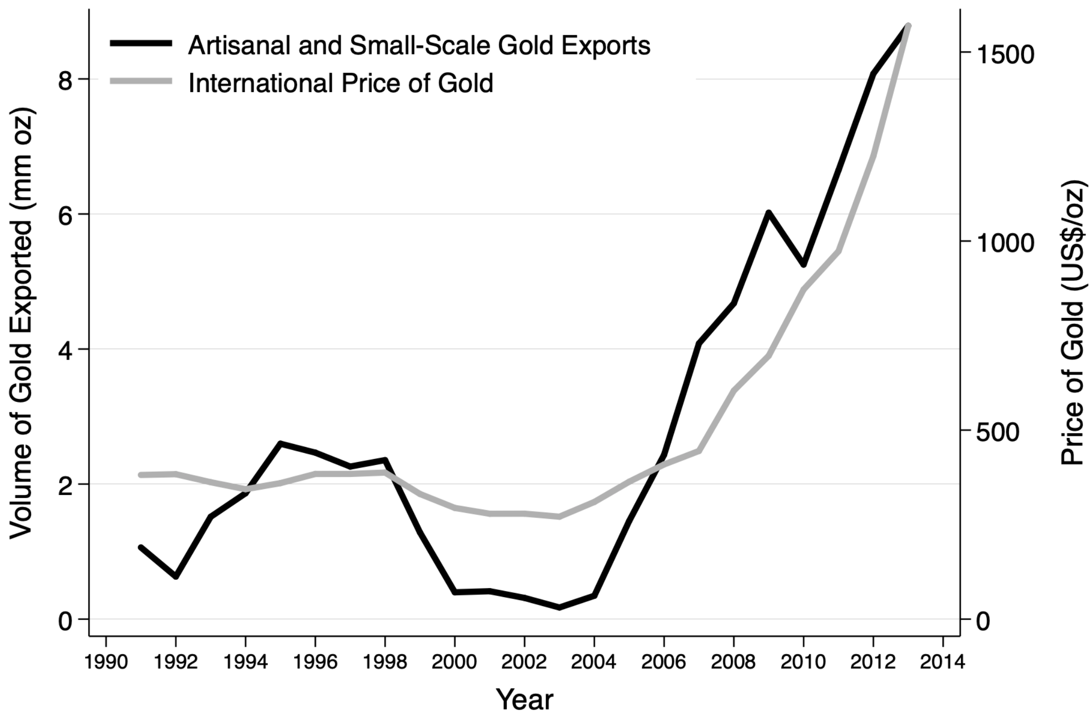
2.1 Overall Context

Peru is one of the world's largest gold producers, among other minerals such as silver and copper.[8] This, due to a particularly rich concentration of ore deposits in the surrounding area of the Andean mountains and the Amazon region, with a long-lasting tradition in mining activity (e.g., Dell, 2010). The overall mining sector in Peru represents approximately 62% of total exports, 12% of GDP, and 30% of state revenues. In the last decades, the production of gold reached a peak of 20% of the world market. And more recently, gold has become the second largest export after copper, with main destination markets, Canada, USA, Switzerland, India, and UAE. Of particular interest, is the size and persistence of informal and illegal gold mining on these exports, which is predominantly produced by artisanal and small-scale gold mines. These producers tend to be highly dependent on international gold prices as suggested by Fig. 1.

Despite the difficulties in measuring informal and illegal mining, official estimates suggest that informal and illegal gold mining reached more than 60% of total Peruvian gold exports at the early 90's, and currently they represent about one third of exports (Global Financial Integrity, 2017). And, even though there has been a reduction in informal and illegal gold mining in relation to the size of formal gold mining, its production capacity has increased over the last decades. As displayed in Fig. 1, the volume of Peruvian gold exports has grown

[8] The country concentrates 18% of world copper production and 27% of silver.

by more than eight times since 1990. In fact, just over the 2000's the area associated with artisanal and small-scale gold mining activity in the Peruvian Amazon, grew approximately 400%, as estimates using satellite images reveal (Asner et al., 2013; Asner and Tupayachi, 2017; Espejo et al., 2018). Which is equivalent to more than 50,000 hectares of Amazon forest loss Asner et al. (2013).



Notes: The figure describes the evolution gold prices and production of artisanal and small-scale gold (formal, informal and illegal) in Peru. This estimated production exported associated to small-scale producers, considers formal, informal, and illegal gold mining. Despite the decrease in the participation of informal mining in total gold production over the last decades from 60% to approximately 30%, the absolute size of the informal sector has increased substantially during the same time.

Figure 1: Artisanal and Small-Scale Gold Production and the Price Boom

While formal mining tends to be concentrated in the north of Peru in close proximity to urban areas, informal and illegal gold mining is usually located in remote areas in the southern and Amazon regions (see Fig. A1). Where small-scale gold-mining is more common and challenging to control due to the difficult accessibility to mining sites. It is estimated that approximately 70% of small-scale gold producers are located in the Amazon region of Madre de Dios (SPDA, 2015). Artisanal and small-scale gold mining is labor intensive, with low technology of production, located in remote areas, and an important source of income for local workers that lacks of profitable alternatives. It is suggested that a worker in an artisanal and small-scale gold mining site can earn about five times the earnings of an agricultural worker in the area studied (Global Financial Integrity, 2017). Recent estimates indicates that around 10,000 workers are employed in the informal and illegal sector in Madre de Dios, and 20,000 indirect workers offer services to these activities in the area (USAID, 2021). With the population of the departments involved in this region growing over the national average.

2.2 The Process of Alluvial Gold Mining

Alluvial gold mining is the most predominant form of artisanal and small-scale gold mining developed in the Amazon region. This type of mining activity encompass formal, informal and illegal gold mining, and is spatially concentrated in the Peruvian region of Madre de Dios. The overall mining process is simple, intensive in labour and land, and with low technological requirements. In a first instance, the process involve forest clearing. This is followed by a stage of hydraulicking, in which the soil is loosen and fractured, filtered in a sluice box, and then washed. A third stage consist of separating the gold particles, in which there is more filtering, and water and mercury washing. Finally, once the gold particles are separated there is a process of amalgamation and dumping of waste residuals. The entire process can lead to a few grams of gold per day for a small-scale gold mine in the area studied, and workers move intensively over the land within a few months in search of more gold.[9] The process is environmentally intensive, inducing long-term consequences such as deforestation, loss of biodiversity, and water poisoning by mercury.

2.3 Formal, Informal, and Illegal Gold Mining

In comparison to formal artisanal and small-scale gold mining, both informal and illegal gold mining lacks of an official authorization to operate, however, informal gold mining is developed in non-protected areas while illegal gold mining operates in protected areas. In practical terms, this implies that workers in illegal gold mining sites are more likely to be arrested and their equipment destroyed by police and military officers. While workers in informal gold mining sites do not face this prosecution. However, informal gold producers still might receive a fine and a lower price for their production in comparison to formal artisanal and small-scale gold producers. This is because trade in informal and illegal gold mining is prohibited by law, and formal producers tend to participate more in cooperatives that have agreements with large intermediaries of gold as part of responsible sourcing initiatives. This in some cases implies that formal mining sites might have a better technology of production with lower environmental impacts and less negative consequences for the health of workers in comparison to informal and illegal artisanal and small-scale gold mining workers.

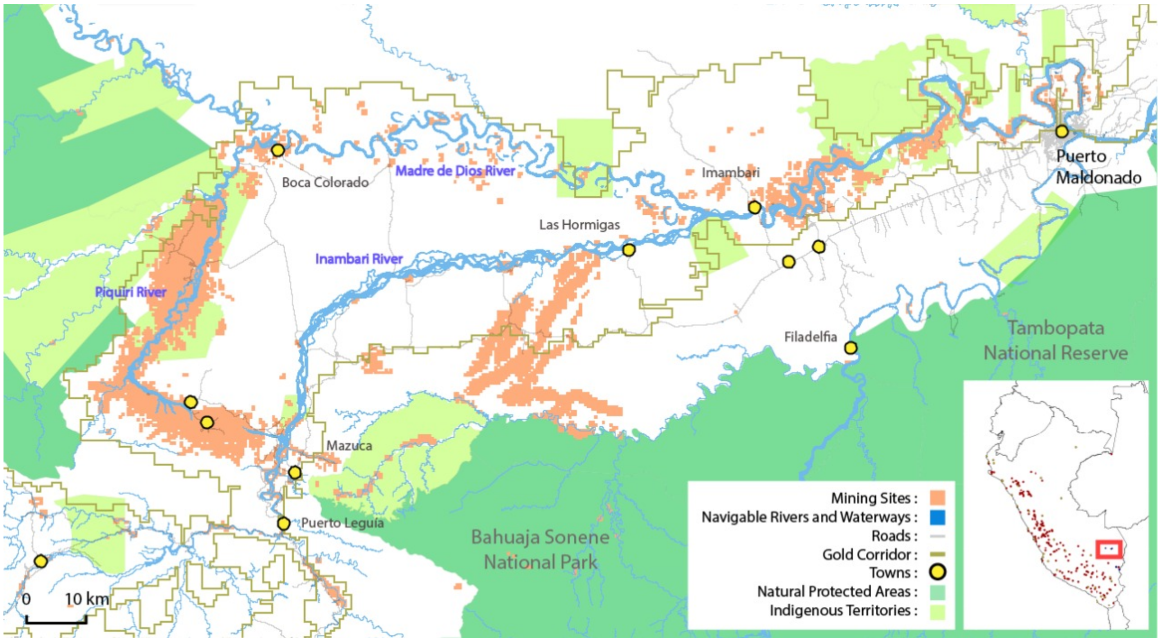
[9]For a mining site of about 30 meters the site is exhausted in less than a year.

The process of formalization of a mining site usually takes several months. This process does not necessarily follows previous registries of land used for other purposes in the area, such as agriculture or forestry. Potentially inducing conflicts for land use rights. Furthermore, anecdotal evidence suggest that some mining concessions might be used to declare the gold produced in illegal mining sites (SPDA, 2015). This is because, a formal concession implies that the mining site has to be exploited, and a minimum amount of production declared, otherwise a penalty proportional to the hectares of the concession is applied to the owner of the concession, according to the Peruvian General Law of Mining.[10] If the penalty is not paid during a period of two years, the concession is revoked. Once the concession is granted, however, producers are required to report at least a minimum amount of gold produced during the following years in order to keep the concession. All these factors implies that the distinction between formal and informal gold mining in the region is diffuse or blurred, as the laws that regulate informal activity are diffuse and started to operate more recently.

Hypothesis 1. *There are differences in the intensity of activity between informal, formal, and illegal gold mining sites. However, differences between formal and informal mining sites tends to be more diffuse.*

The distinction between illegal and non-illegal –considering formal and informal– mining is more evident. In part because natural protected areas are defined earlier in the sample and they are more easy to be distinguished geographically (see Fig. A2 for the official boundaries of mining concessions and protected areas in the Peruvian Amazon). According to qualitative surveys, the organization of workers in the artisanal and small-scale gold mining sector in the region tends to be decentralized (SPDA, 2015). From the group of workers in a given mining site, one is usually exploring for new areas to develop, while they also move as a response to inspections by police and military authorities. This in comparison to non-illegal –considering formal and informal– gold mining, in which workers tend to stay more mining their sites and move to other places as they exhaust the land in the area. Workers usually move in small camps and follows the gold track found by other miners. For the case of formal and informal mining, this occur within the geographical boundaries of the so-called *"corredor minero"* (mining corridor). The area delimited by the government as authorized to be exploited. However, most of illegal gold mining falls within natural protected areas and the *"zona de amortiguamiento"* (buffer zone), a geographical belt between the mining corridor and natural reserves.

[10] More precisely, these laws are stipulated in: DL No. 1320 and DS No. 011-2017-EM.



Notes: The figure shows the artisanal and small-scale gold mining sites (area in orange) in the Peruvian Amazon region of Madre de Dios, where it is estimated that about 70% of Artisanal and Small-Scale Gold Mining in Peru is produced. Unless specified in the data of mining concessions (see Fig. A2), in general non-illegal gold mining sites are defined as sites that fall within the boundaries of the "Mining Corridor" (polygon with golden borders). Almost all mining sites outside of this polygon are defined as illegal mining sites. These include mining sites that are in the "Buffer Zone", the area between the Mining Corridor and the Protected Natural Parks, and mining sites within the boundaries of Natural Protected areas and some in Indigenous Territories. For mining sites within the boundaries of the Mining Corridor, data from Mining Concessions from the Peruvian Ministry of Mines (see Fig. A2) allows the identification of those that are formal (with a concession granted), or informal (without a mining concession).

Figure 2: Artisanal and Small-Scale Gold Mining in the Peruvian Amazon Region

2.4 Policy Making

Major policy efforts regarding formalization and control of illegal gold mining activity in the Peruvian Amazon started in the 2000's, with the boom of commodity prices. In part, motivated by the visible large impacts on deforestation caused by gold mining activity. Before these reforms were implemented, the activity was practically unregulated. Informal and illegal gold mining developed in the Amazon during that time without major restrictions in spite of the geographical delimitation of natural protected areas, and the existence of mining concessions and rights for different land uses in the region dating back to 1977.[11] It was not until 2002 that the first major reform to formalize the activity was implemented proceeded by a series of reforms that did not have a major impact on the activity, as gold mining continue

[11]Before 2000's, the Peruvian government has not many incentives to discourage gold mining activity in the Amazon region. Given that this activity induce important growth of the population in the region. And there were geopolitical interests in avoiding occupancy of these lands by Brazilian forces.

to spread in the area..[12]

A major reform towards the formalization of gold mining activity in the region was implemented in 2011. During this process miners could request a concession over a certain area that automatically granted them with the legal right to exploit the mining site. After the concession was requested, miners had a period of three years to actually complete the process of formalization. In the years following this reform, a large number of concessions were requested. However, this policy was heavily criticized because it was perceived that illegal gold producers could have taken advantage of these concessions to declare their exploitation from other sites, as a form of money laundering. This process of formalization finished in 2014, and after that year any new request for concessions requires a slightly more rigorous control. Under this new strategy of regulation, the existing and new mining concessions in the area face a more strong law enforcement, and illegal gold mining activity more control. These controls involve police and military raids, the destruction of mining equipment of illegal producers, and clashes that occasionally result in casualties.[13]

Hypothesis 2. *Price elasticity is high and tends to be larger for illegal mining sites, capturing the lower costs of being informal or illegal.*

3 Data

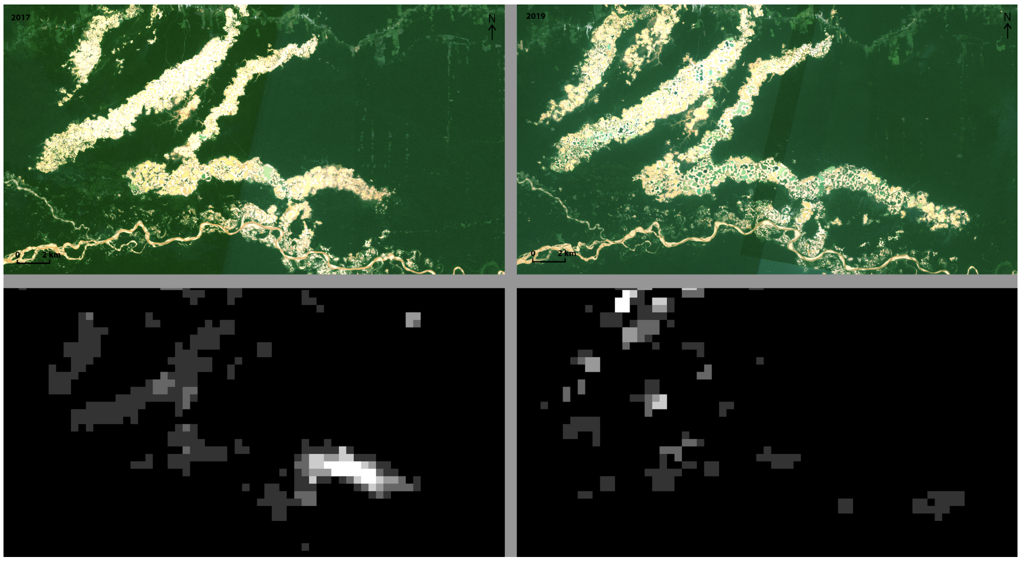
3.1 Identifying and Measuring Alluvial Gold Mining Activity

To measure the activity of each mine, I adopted a variation of the strategy pioneer in the work of Hodler and Raschky (2014), and subsequently followed in Berman et al. (2017), Mamo et al. (2019), and Saavedra and Romero (2021), among others. Specifically, I use a composite measure of nightlights data (MODIS) and spectral information from medium-resolution satellite images (≈500 meters), to construct a proxy of the intensity of mining activity within each site. This measure is validated by exploring the correlation with production of formal gold mining in the Amazon region of Madre de Dios, reported by the Peruvian Ministry of Mines (MINEM) . This strategy provides a large number of observations of monthly data between

[12] DL. 27,651 and DS. No. 013-2002-EM.

[13] Despite the existence and growing of the number of conflicts induced by mining activity in the Amazon region, these are low in magnitude and not comparable to the reported in the empirical literature for the African region (e.g., Berman et al., 2017), or for other Latin American countries, such as Colombia and Venezuela. Empirically, however, these concerns will be addressed by proxying for the likelihood of such events in mining sites.

January 2014 and December 2018, for approximately 4,000 mining sites identified in the Peruvian Amazon region.[14]



Notes: The figure describes the distribution of nighttime lights value of mining sites according to the categories identified with the registry of mining concessions and protected areas for the period between 2014 (light colours) to 2018 (darker colours). Each mining site ($n = 369,017$) represent an area of approximately 30m2 for which the value of nighttime lights from MODIS is represented. The mining site is considered active when it is reported a positive value of nighttime light. Vertical lines represent average values for each category. Formal mining sites ($n = 211,596$) are pixels that are within areas with a registered valid concession. Informal mining sites ($n = 97,127$) are pixels without a registered valid concession area but in areas authorized for mining activity, denoted as the *"corredor minero"*. Illegal mining sites ($n = 60,294$) are pixels within protected natural parks and indigenous land.

Figure 3: Intensity of Activity in Mining Sites

3.2 Defining Formal, Informal, and Illegal Mining Sites

Once mining sites are identified using satellite information, the layers of official data from protected areas and the mining cadastral from the Peruvian Ministry of Mines, are used to classify each pixel identified as a mine (see Fig. A2). Whenever a pixel is within the boundaries of a protected area, the mining site is classified as illegal. When the site falls within the boundaries of cadastral areas registered as concessions, the information of this concession is added to the pixel. This information contains the date in which the concession was granted. In this case, an informal mine can become formal during the period studied, or become in-

[14]The large number of observations is key to estimate the price channels because it gives enough power to identify the interactions between prices and a series of variables capturing these different channels of the supply chain. This form of using pixels as unit of observation is also used in Berman et al. (2017). Here the claim is more simple because those pixels were already identified as part of mining sites by a machine learning classification algorithm, as in the work of Soto-Díaz (2022).

formal if the concession has expired. Finally, when the pixel is outside any of these areas, the mine is classified as informal. This follows closely the definition and classification of mines used by Peruvian authorities.[15]

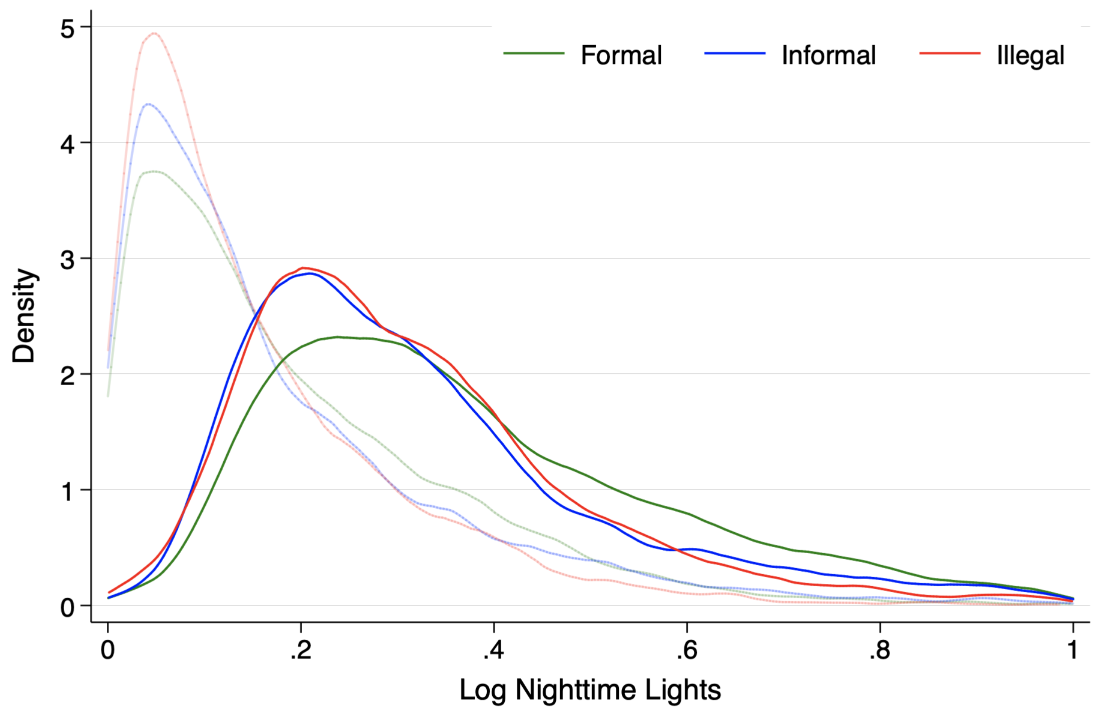


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Figure 4: Intensity of Activity in Mining Sites

[15] Almost 15% of cadastral registry surface is overlapping other mining concessions. In addition, some of these concessions are also overlapping forest land use for production and forests concessions (see Fig. A2). A small number of areas of mining concessions overlap protected natural reserves or areas of indigenous land, and an area called *"zona de amortiguamiento"* (buffer zone). A protected land area between the natural protected areas and the mining corridor.

4 Empirical Evidence

The empirical strategy is divided into two parts that aims to give comprehensive evidence on the case studied. First, the differences in activity between informal relative to formal, and illegal relative to non-illegal gold mining sites are estimated. Secondly, given the significant differences reported, the heterogeneous responses in the activity between illegal and non-illegal gold mining sites to the international price of gold are further explored.

4.1 Estimation Strategy

4.1.1 Relative Differences between Gold Producers

To test for the existence of differences between formal, informal, and illegal gold mining activity, previously defined in Subsection 3.2, two set of regressions are estimated. The first set compares informal gold producers relative to formal gold mining, while the second set compares illegal gold producers relative to non-illegal –considering formal and informal– gold mining. More precisely, these differences are estimated with the following specification

$$\log y_{ot} = \alpha + \delta D_{ot} + \theta_d + \theta_t + \theta_{dt} + \mathbf{X}'_{ot}\Gamma + \eta_{ot}, \tag{1}$$

where D_{ot} is an indicator function to categorize the mining site as informal (relative to formal), or illegal (relative to non-illegal). θ_d are district fixed effects, θ_t are month fixed effects, θ_{ot} are district–by–month fixed effects, $\mathbf{X}'_{ot}$ is a vector of geographic coordinates, and η_{ot} denote an idiosyncratic error term. Given the set of fixed effects included in Eqn. 1, the identification of the differences between gold mining sites relies on the spatial variation within each district in each month, balancing the observations by their precise location. However, to have a better understanding of the differences between formal and informal gold mining activity, it is possible to exploit more the temporal variation within each mining site. More precisely, to exploit the fact that some mining sites operating in the sample become formal. Accordingly, an event study was implemented using this sub-sample of observations with the following staggered Diff-in-Diff specification,

$$y_{ot} = \alpha + \sum_{k=-m}^{-1} \delta_k D_{ot} + \sum_{k=0}^{m} \delta_k D_{ot} + \theta_o + \theta_t + \eta_{ot}, \tag{2}$$

where the event is determined by the month in which the formal mining concession was registered as granted. The results reported use the Sun and Abraham (2020) correction for the potential negative weights in the estimates given by heterogeneous treatment effects. In Eqn.

2, the identification of the differences in the intensity of mining activity between informal and formal gold mining sites came from the temporal variation in the timing of formalization. Given that mining sites tend to be operating for periods usually no longer than a year, this exercise will compare the differences in the five months previous and after the formalization. Specifically, as the date in which the concession is registered according to the mining cadastral of the Peruvian Ministry of Mines.

4.1.2 Price Elasticities

Once the differences between gold mining sites has been documented, the following section will interact those differences with the international monthly price of gold. This constitutes the key component of empirical evidence behind the motivation of this paper, i.e., to understand how illegal gold mining activity in relation to non-illegal gold mining responds to shocks to the international price of gold. More precisely, the existence of heterogeneous effects of the price of gold on the activity of illegal and non-illegal mining sites are tested in the following specification

$$\log y_{ot} = \alpha + \beta \log Price_t + \delta D_{ot} + \lambda (D_{ot} \times \log Price_t) + \theta_d + \theta_t + \theta_{dt} + \mathbf{X}'_{ot}\Gamma + \eta_{ot}, \quad (3)$$

where D_{ot} is an indicator function for illegal mines relative to non-illegal gold mining sites (considering formal and informal sites). θ_d are district fixed effects, θ_t are three-month-period fixed effects, θ_{dt} are three-month-period by district fixed effects, Γ is the vector of geographic coordinates, and η_{ot} the error component. The identification of these heterogeneous effects rely on the exogeneity of the international price of gold, and the spatial differences in the intensity of mining activity across mining sites.[16]

In order to identify the level of the price effect, given that this vary on a monthly basis, the time and time-by-district fixed effects consider a three-month period window. Fig. A3 shows the variation in the international price of gold and average nighttime lights within these three months period windows. There is important variation, of about 25%, within a few months in the price of gold and intensity of activity in mining sites. In addition, it also shows the absence of particular trends during the period analyzed. Notwithstanding, the results with the full sets of fixed effects considering month and pixel fixed effects are also reported.

[16] Even considering that Peru is a large gold exporter, there is no evidence that they affect the international price of gold. Moreover, considering that these observations represents artisanal and small-scale gold producers.

4.2 Results

4.2.1 Relative Differences between Gold Producers

Consistent with the previous descriptive evidence, results in columns 1 to 3 of Table 1, shows that informal mining sites tend to be associated with lower nighttime light intensity in comparison to formal mining sites. However, this difference is not statistically significant. As described in Subsection 2.3, this is likely explained by the diffuse institutional boundaries that distinguish informal and formal small-scale gold mining activity. In other words, the lack of regulation of informal mining sites might induce the similar intensity of activity with formal mining sites. On the other hand, when illegal mining sites are compared with non-illegal –considering formal and informal– sites in Columns 4 to 6 of Table 1, the difference is statistically significant and robust to the inclusion of fixed effects and geographic coordinates. These estimates suggest that illegal mining sites are associated with approximately 4% less of nighttime lights intensity in comparison to non-illegal gold mining sites.

The reasons for these results evidencing more differences when comparing illegal to non-illegal gold mining sites than informal relative to formal sites can be various. However, a main argument is that the institutional boundaries that define informal relative to formal gold mining are more diffuse than those that define illegal relative to non-illegal gold mining. Specifically, as commented in the description of the case study, informal gold mining activity in the region is not usually prosecuted. As it is illegal gold mining. Then, informal miners can stay exploiting their site as long as they pay the fine if they are denounced to authorities. Or if they do not face opposition from landowners, people with other concessions or the local population. In comparison, illegal gold miners can face prison and their equipment destroyed when they are caught by authorities. This implies that they have to move more quickly over the land as they mine, to avoid the police force, and they have to smuggle their equipment and production to avoid being caught in the rivers and roads. As the commerce of fuel –and mining equipment– is banned over a certain threshold in those areas.

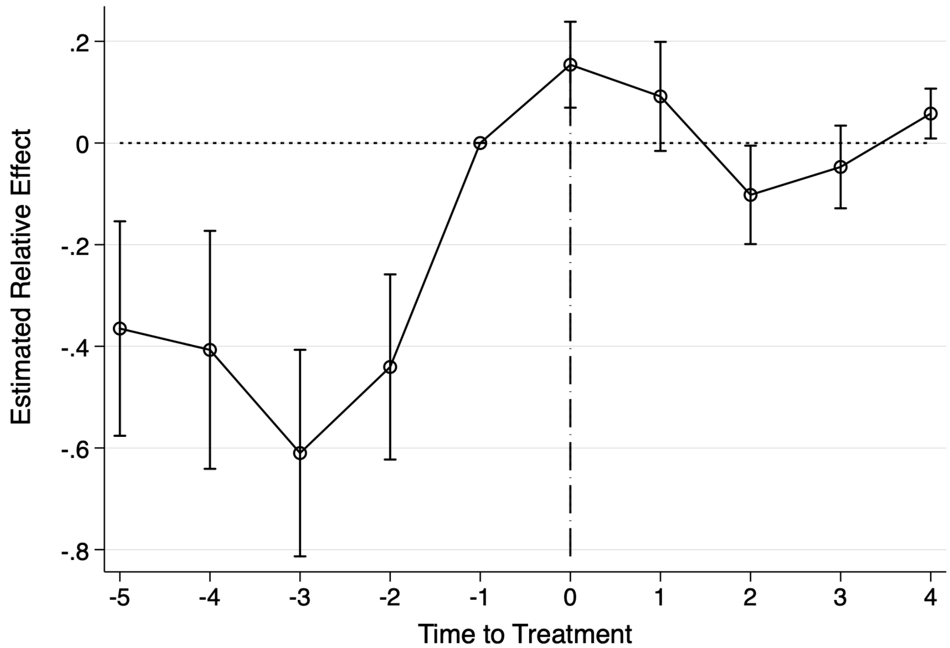
Despite the non-significance of the differences between informal and formal gold mining sites in the area when relying on spatial variation, the event study on formalization in Fig. 5 reveals a more clear picture of the differences between these producers. Specifically, the estimates that rely on the temporal variation in the timing of formalization of a sub-sample of previously informal mining sites, shows that in the five months before the formalization was granted, informal mining sites tends to have a lower nighttime light intensity relative to formal mining sites. However, once the formalization was granted those differences disappear and become non-significant in the five months after the formalization.[17] Which indicates

[17]There were not enough observations to run the event study over a longer period. In most of cases, the mine

Table 1: Differences between Gold Mining Sites

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Informal (=1)	-0.015	-0.020	0.002	0.003	0.006					
	(0.014)	(0.015)	(0.013)	(0.013)	(0.011)					
Illegal (=1)						-0.065*	-0.070*	-0.040**	-0.039**	-0.038***
						(0.034)	(0.038)	(0.016)	(0.015)	(0.012)
Month FE		✓	✓	✓	✓		✓	✓	✓	✓
District FE			✓	✓	✓			✓	✓	✓
Month × District FE				✓	✓				✓	✓
Geographic Coord.					✓					✓
Constant	0.299***	0.301***	0.294***	0.293***	32.088**	0.294***	0.295***	0.290***	0.290***	29.655***
	(0.035)	(0.038)	(0.004)	(0.004)	(13.674)	(0.032)	(0.035)	(0.003)	(0.002)	(10.023)
Adjusted R^2	0.001	0.152	0.229	0.264	0.275	0.010	0.172	0.241	0.275	0.285
Observations	421,447	421,447	421,447	421,384	421,384	505,070	505,070	505,070	505,009	505,009

Notes: $*p < .10$, $**p < .05$, $***p < .01$. Standard errors in parenthesis. Standard errors are clustered at the district level. Each observation correspond to a 30m pixel identified as a mining site in a given month between January 2014 and December 2019. In columns (1) to (3), Informal (=1) is compared to only mining sites identified as formal, and illegal mining sites are dropped from the sample. In Columns (4) to (6), Illegal (=1) is compared against mining sites identified as non-illegal (considering both formal and informal).



Notes: The figure displays the results of an event study using the mining sites before and after the mining concession was granted. Using nighttime lights and the mining cadastral registry. The time to treatment is measured in months from the mining concession is registered. The y-axis show the estimated relative effect of formalization in comparison to mining sites that are formal during the period. I.e. previous the concession was registered, there were significant differences between informal and formal mining sites, but those differences in nighttime lights disappear once the concession is registered. Given that protected areas are defined previous to the sample period, it is not possible to make an event study over the illegal mining sites.

Figure 5: Event Study on Formalization

that formalization of previously informal mining sites led to a higher activity relative to what nighttime lights reveal previous to the formalization. These results might be explained by informal miners adopting better technologies in their production that are captured by nighttime light intensity.

What we have uncover so far is the formalization costs, by relying on time variation in the legalization of the mine. And the trade cost, relying on spatial variation in the construction of roads (cross-sectional results) for intermediaries. And for producers. This evidence, relying on the temporal variation in formalization of previously informal mining sites, suggest that at least during the five months previous to the month in which the formalization was granted, informal mining sites shows a lower intensity in nighttime lights in comparison to formal mining sites. This difference is statistically significant and of about 4%. However, once the formalization is granted, those differences in intensity of activity in mining sites between

started to operate once the concession is granted, and therefore, there are not many pre-treatment observations as observations used in Table 1.

informal and formal producers disappear in the following months.

Results are indicative evidence supporting the hypothesis that formal mining sites might being used to declare illegal gold mine from other sites. As an individual or a group of individuals can request a formal mining title over areas that are not necessarily highly productive in terms of the gold endowment. Then, can declare the gold from illegal mines as extracted from formal sites. In this case once the mining site is formalized, there is no need for continue to mine the site, and therefore, the decrease in nighttime lights intensity after the formalization is granted. However, despite these patterns observed yearly, there are too few observations per month to make a substantial claim on this point of formalization. In most of cases, the mine started to operate once the concession is granted, and therefore, there are not many pre-treatment observations so this evidence should be considered as suggestive.

4.2.2 Price Elasticities

More importantly, the results regarding the effect of the gold price on the intensity of activity in mining sites, and how the differences in the intensity of activity between illegal and non-illegal gold mining sites respond to variation in the price of gold are reported in Table 2. The price elasticity is positive, economically and statistically significant, and robust among different specifications. The magnitude of this coefficient is about 0.5. These results are consistent with Fig. 1, suggesting that artisanal and small-scale gold mining activity is highly sensitive to variations in the international price of gold. More specifically, a price boom as the represented in Fig. 1 that increase the gold price by approximately 3, is estimated to have increased overall artisanal and small-scale gold mining by 1.5 times.

Interesting is to observe the heterogeneous effects of the price of gold between illegal and non-illegal producers. As the descriptive evidence previously suggested, illegal gold mining sites have significant lower intensity in mining activity. However, this difference is reduced as larger the price shock. Meaning that for high values of gold prices the difference in nighttime lights intensity between illegal and non-illegal producers disappears. This is more clearly represented with the marginal effects of gold prices, reported in Fig. 6.[18] This difference against illegal gold producers disappears for high values of the international price of gold. As displayed in Fig. 1, the last price boom implied an increase in the price of gold by three times. In comparison, an increase in the price of gold of about 30% from the average in the sample, would lead to an increase in the intensity of illegal mining activity over the levels of legal small-scale gold mining in the Amazon region. In further analysis non-linear effects of the price of gold on the intensity of activity in mining sites were explored but found to be not

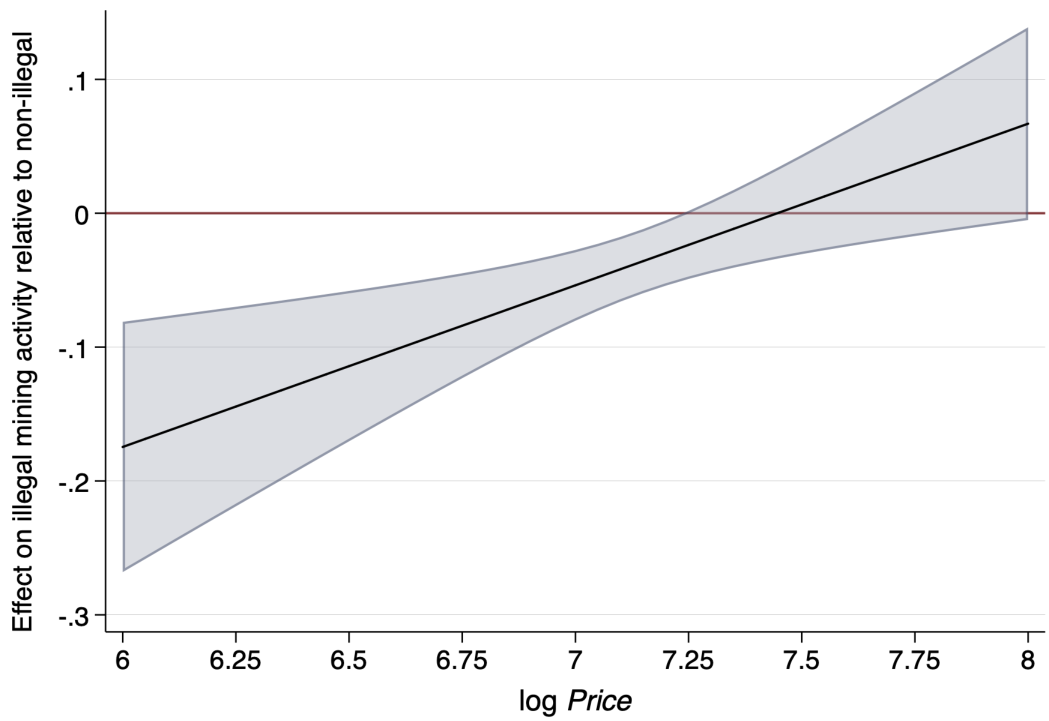
[18]Nonlinear effects were estimated but founded non-significant.

Table 2: Price Elasticities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
log *Price*	0.664***	0.671***	0.646***	0.432***	0.514***	0.516***	0.537***
	(0.032)	(0.034)	(0.036)	(0.146)	(0.120)	(0.128)	(0.135)
Illegal (=1)		-0.066*	-1.180***	-1.116***	-0.883**	-0.992***	-0.899***
		(0.035)	(0.240)	(0.235)	(0.323)	(0.283)	(0.289)
Illegal (=1) × log *Price*			0.156***	0.147***	0.118**	0.134***	0.121***
			(0.038)	(0.036)	(0.047)	(0.040)	(0.040)
Three-Month Period FE				✓	✓	✓	✓
District FE					✓	✓	✓
Three-Month Period × District FE						✓	✓
Geographic Coord.							✓
Constant	-4.452***	-4.488***	-4.310***	-2.781**	-3.375***	-3.390***	25.677**
	(0.221)	(0.231)	(0.236)	(1.072)	(0.860)	(0.913)	(9.500)
Adjusted R^2	0.021	0.032	0.032	0.134	0.202	0.217	0.227
Observations	505,070	505,070	505,070	505,070	505,070	505,067	505,067
	(8)	(9)	(10)	(11)	(12)	(13)	(14)
log *Price*	0.646***				0.768***		
	(0.036)				(0.030)		
Illegal (=1)	-1.180***	-1.034***	-0.794**	-0.736*			
	(0.240)	(0.270)	(0.376)	(0.377)			
Illegal (=1) × log *Price*	0.156***	0.135***	0.106*	0.098*	0.089**	0.070	0.043
	(0.038)	(0.042)	(0.054)	(0.054)	(0.038)	(0.048)	(0.050)
Month FE		✓	✓	✓		✓	✓
District FE			✓	✓			
Month × District FE				✓			✓
Pixel FE					✓	✓	✓
Constant	-4.310***	0.295***	0.290***	0.290***	-5.298***	0.201***	0.232***
	(0.236)	(0.035)	(0.003)	(0.002)	(0.192)	(0.056)	(0.058)
Adjusted R^2	0.032	0.172	0.241	0.275	0.404	0.588	0.623
Observations	505,070	505,070	505,070	505,070	505,070	505,067	505,009

Notes: $^{*}p < .10$, $^{**}p < .05$, $^{***}p < .01$. Standard errors in parenthesis. Standard errors are clustered at the district level. Time of observations is monthly. Each observation correspond to a 30m pixel identified as a mining site in a given month between January 2014 and December 2019. Illegal (=1) is compared against mining sites identified as non-illegal (considering both formal and informal).

statistically significant.



Notes: The figure presents the marginal effects of gold price from Column (6) in Table 2. The y-axis shows the difference in the intensity of mining activity measured with nighttime lights between illegal and non-illegal mining sites.

Figure 6: Marginal Effects of Gold Price

5 Conclusion and Policy Implications

To shed light on the relative responses of informal and illegal mining in relation to formal mining in the wake of large foreign demand shocks, this paper estimates the differences in the intensity of mining activity between formal, informal, and illegal small-scale gold producers in the Peruvian Amazon, and how these differences respond to variations in the international price of gold. First, results show important and robust differences in the intensity of mining activity between illegal and non-illegal gold mining producers on average of about 4%, but negligible differences between informal and formal producers. However, an event study using a sub-sample of previously informal mining sites that formalized in the period study, shows that in the months before the formalization of the site, informal mining display an average 4% lower nighttime light intensity than formal mining. But once the mining site is formalized those differences disappear in the following months after the concession of the site was granted.

Second and more importantly from a policy perspective, the evidence shows that the intensity of activity of artisanal and small-scale gold producers is highly sensitive to variations in the international price of gold, with a price elasticity of approximately 0.5 to 0.8 across the different estimates and robust to the inclusion of a wide set of fixed effects. Moreover, these effects are highly heterogeneous between illegal and non-illegal producers, suggesting that a price boom of about a 25% increase relative to the average price level make disappear the differences between illegal and non-illegal producers in nighttime lights intensity . Such price variations are observed in the sample within short periods of time of less than a year. More precisely, results suggest that a significant price increase can lead to more a than proportional rise in illegal gold mining activity relative to non-illegal gold mining. This is arguably, a result of a rise in the profitability of this activity.

The results have important policy implications. On the one hand, the current policy approach to discourage illegal gold mining activity in the Peruvian Amazon is based on artificially increasing their costs of production in order to reduce the profitability of this activity. For this purpose, authorities banned the commercialization of mercury and fuel in the area of illegal gold mining. However, the activity has continue spreading in the Peruvian Amazon over the recent years. Despite that the economic logic of this policy approach is right and might lead to a decrease in the profits of illicit mining activity and consequently a decrease in illegal activity, the results in this paper suggest that the incentives to do illegal gold mining are too large and are highly responding to international demand shocks. In other words, the high price elasticities reported in relation to the activity of small-scale gold producers suggest that these are more likely to respond to policies that target their marginal income.

The implications of these results is that authorities can have a more significant impact by also using policies that affect the local price of illegal gold relative to non-illegal gold. Specially, policies that reduce the effect that certain unexpected shocks in the international price of gold might have in rising the profitability of illegal gold mining. This kind of policies might reduce the elasticity that it is found in the estimates. In order to do this, the government might consider regulating the market of gold intermediaries, as they are the main buyers of this illicit gold. On the other hand, they can promote policies of fair trade that increase the profitability of formal mining relative to informal and illegal gold mining. However, more research is needed to quantify the impact of those policies. Specially on the role of intermediaries in these supply chains.

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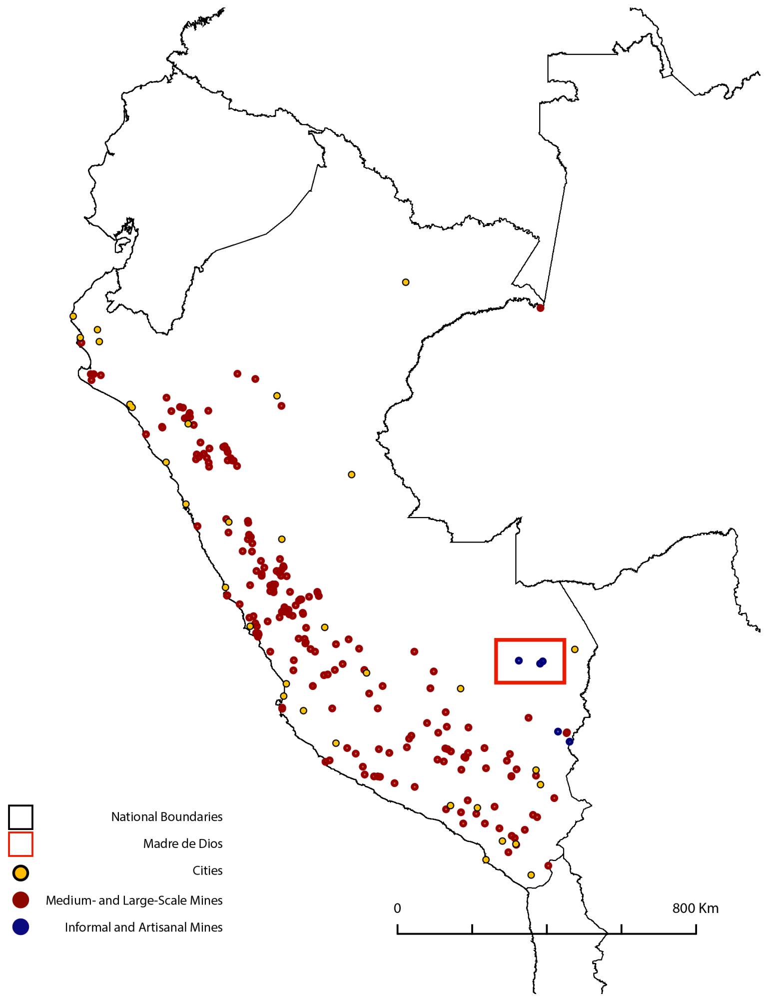
Appendix



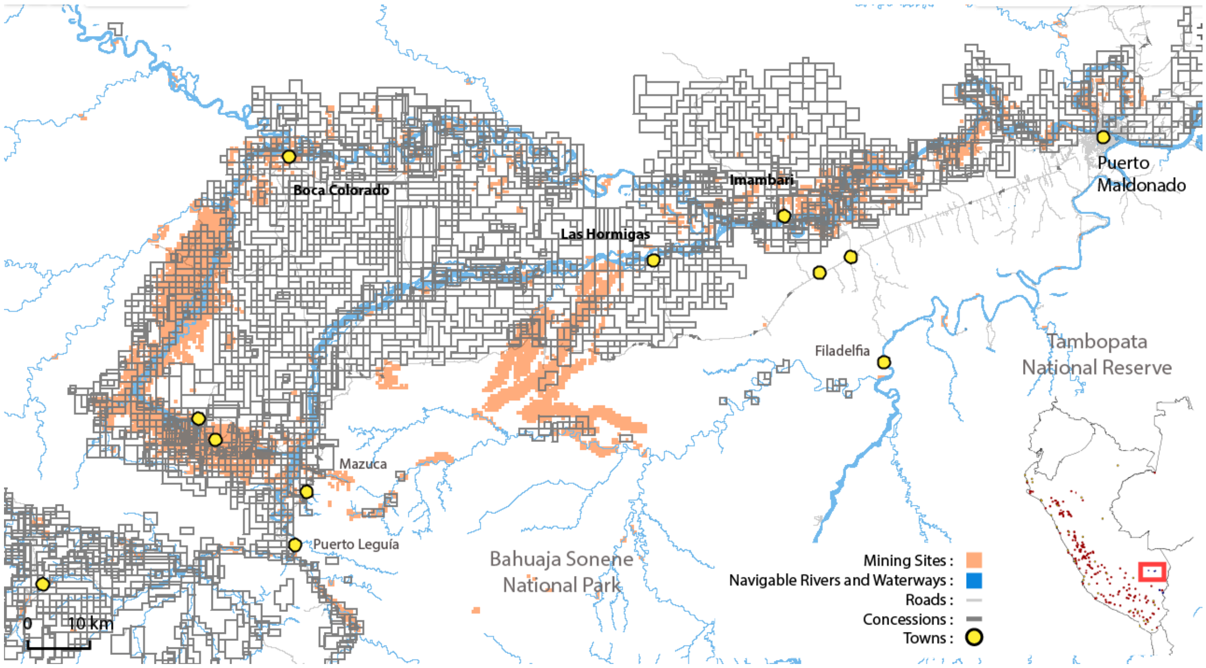
Notes: The figure shows the spatial distribution of cities represented by yellow dots (with a population greater than 25,000 inhabitants), and mines. Medium- and large-scale mines are represented by red dots while small-scale informal and artisanal mines are represented by blue dots. The area of study, "Madre de Dios" is highlighted by the red box. Small-scale informal and artisanal mining is concentrated in the south of Peru and Amazon region, and in gold mining. Where the region represents about 70% of small-scale and artisanal gold exports. While medium- and large-scale mining is more spread across the Andean region and in more close proximity to urban areas.

Figure A1: The Geography of Mining in Peru

Table A1: Descriptive Statistics

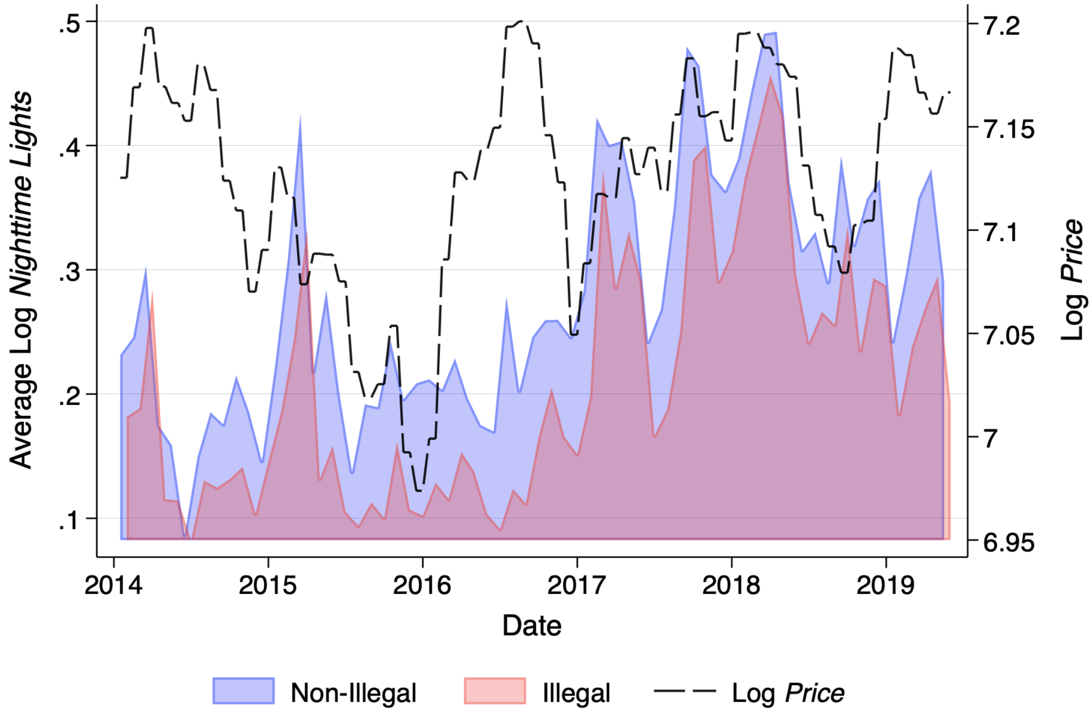
Type	Mean	SD	Median	Min	Max	Observations
Formal	0.276	0.236	0.224	8.09E-06	2.700	211,596
Informal	0.263	0.265	0.196	8.09E-06	3.336	97,127
Illegal	0.207	0.176	0.168	1.27E-05	2.040	60,294
Overall	0.261	0.237	0.206	8.09E-06	3.336	369,017

Notes: The table shows the descriptive statistics of the nighttime lights variable for each one of the type of artisanal and small-scale gold mining sites in the area studied.



Notes: The figure displays the land concessions in the area of study. Each polygon represents a land concession granted. Mining concessions that overlap with mining sites identified with satellite images, are classified as formal mining sites if the period during the site was operating as measure by nighttime lights coincides with the period in which the mining concession was active. Otherwise, if the concession was not active during the period of exploitation, then the mining site is defined as informal. These concessions are spatially distributed under the area defined as the "Mining corridor". With a few exceptions, mining sites identified with satellite images that falls outside this mining corridor are illegal mining sites.

Figure A2: Mining Concessions and Protected Areas



Notes: The figure describes the average monthly temporal variation in activity within illegal and non-illegal mining sites, and the average monthly international price of gold during the period study. As a reference of the important price variation within short periods of time, it can be seeing that just within a period of about six months in 2016, the price of gold increase by approximately 25%, while the same decrease was observed between 2014 and the end of 2015.

Figure A3: Variation in International Gold Price and Activity in Mining Sites