

GOVERNANCE, TARGET, AND PLACE: RATIONAL DETERMINANTS OF ILLEGAL MINING IN THE BRAZILIAN CAATINGA

1 INTRODUCTION

This research seeks to develop an econometric model to assess the risk of illegal mining activities in Brazil's Caatinga biome using a framework based on the rational choice theory (Becker, 1968; Ehrlich, 1973) and the three elements of routine activity theory (Cohen & Felson, 1979). Becker's classical criminology theory, grounded in Enlightenment principles, views criminal behavior as a rational, deliberate choice (Becker, 1968). This economic perspective considers the balance between perceived benefits and risks in criminal decision-making. To Becker's model, Ehrlich (1973) added controls for legal and illegal income opportunities, creating the so-called Becker-Ehrlich model, described below in its usual logarithmic form (Entorf & Spengler, 2000):

$$\ln(\text{crime rate}) = \beta_0 + \beta_1 \ln(\text{deterrence}) + \beta_2 \ln(\text{income}) + \beta_3 \ln(\text{other influences}) + u$$

Complementarily, the routine activity theory (Cohen & Felson, 1979) asserts that crime materializes when an offender, target, and place converge in the absence of a capable guardian. Later, Clark and Eck (2009) expanded this theory by introducing governance elements: a handler influencing the offender and a manager overseeing the place.

Using these theories as framework, this study employs generalized linear regressions to enhance the understanding of the dynamics driving illegal mining activities in Brazil's Caatinga region, analyzing data across a 10km² grid over the average values of an eleven-year period (2010-2020). The main goal is to unravel the intricate relationships between governance efficiency (offender), mineral desirability (target), and geographical attributes (place) in facilitating illegal mining.

This approach could provide actionable insights for public agencies, including transitioning from reactive to proactive approaches in resource and staff allocation, and identifying high-risk areas for illegal mining. Moreover, public disclosure of areas susceptible to illegal mining could deter environmental crimes by influencing potential offenders' cost-benefit analyses, considering the risks of legal sanctions or reputational damage. Finally, publicizing municipalities at a higher risk for unauthorized mining might replicate the success of early 2010s strategies used in the Amazon to curb environmental offenses (Assunção & Rocha, 2019).

At the core of this inquiry are three hypotheses. The first investigates the efficacy of governance mechanisms as deterrents to illegal mining, examining the role of environmental and mining governance, and law enforcement in curbing such activities (Soares & Naritomi, 2007, p. 2). Data primarily acquired from Federal Police environmental investigations, and fines applied by the environmental and mining regulation agencies provided the empirical foundation for testing this hypothesis, offering critical insights into the capacity of existing governance structures to deter illegal mining activities (H1).

The second hypothesis delves into the suitability of minerals as a target for illegal miners. This hypothesis introduces the concept of Mining-Related Illegal Income (MRI) as a proxy for opportunities of illegal income (Ehrlich, 1973). The idea is that the suitability of a mineral (the target) for criminal activity directly increases the potential for illicit financial gain. Hence, based on the CRAVED approach (Moreto & Lemieux, 2015), a metric was created to test the impact of attractiveness of minerals on illegal mining, especially regarding their Value, Abundance, Localization, Use, Explorability and Disposability. This method is henceforth referred as the VALUED approach.

The third hypothesis examines the geographical determinants of mining tenements, proposing a positive correlation between infrastructure attributes (H3), such as roads and gas stations, and the presence of legal mining nearby (H3.1). This hypothesis broadens the Becker-

Ehrlich deterrence model to include spatial variables, thereby deepening our understanding of the determinants behind illegal mining activities.

2 METHODOLOGY

This study evaluates the risk of illegal mining in the Caatinga biome by integrating the Becker-Ehrlich econometric model with environmental criminology concepts, particularly the routine activity theory. It operationalizes the theory's components—governance of miners (offender), mineral desirability (target), and mining tenements' geography (place)—within the following econometric model framework:

$$\text{Illegal mining} = \beta_0 + \gamma_1(\text{Governance Over Miners}) + \gamma_2(\text{Target Suitability}) + \gamma_3(\text{Place Suitability}) + u$$

Where:

$$\begin{aligned} \gamma_1(\text{Governance Over Miners}) &= \beta_1(\text{Police Investigations}) \\ &+ \beta_2(\text{Environmental Fines}) + \beta_3(\text{Mining Fines}) \\ &+ \beta_4(\text{Opportunities for Legal Income}) \\ \gamma_2(\text{Target Suitability}) &= \beta_5(\text{Opportunities for Illegal Income}) \\ \gamma_3(\text{Place Suitability}) &= \beta_6(\text{Roads}) + \beta_7(\text{Gas Stations}) \\ &+ \beta_8(\text{Urban Area}) + \beta_9(\text{Mineral Occurrences}) \end{aligned}$$

The model was tested employing Generalized Linear Regression (GLR) on ArcGIS Pro 3.1., further augmented by the inclusion of a spatial lag control (8 k-nearest neighbors) to account for the spatial distribution of data. After gathering all data collected from 2010 to 2020, the values were spatially aggregated using the arithmetic mean for each cell. In alignment with the original equation proposed in the Becker-Ehrlich model, where all variables are expressed in natural logarithmic form, after aggregation, the following natural logarithmic transformation was applied to all variables:

$$f(x) = \begin{cases} \ln(x + 1) & \text{if } x > 0 \\ -\ln(|x| + 1) & \text{if } x < 0 \\ 0 & \text{otherwise} \end{cases}$$

The study analyzed a grid of 10 km² cells covering all 936 municipalities completely within the Caatinga biome. This analytical unit, chosen to mitigate endogeneity and enhance robustness and comprehensiveness, follows the methodological insights of Berman et al. (2017). The analysis centered on the 33,990 cells containing mining tenements that requested permission to extract one of the ten most demanded minerals in Brazil from 2010 to 2020, as documented in the National Mining Agency (ANM) database: Clay, Copper, Gold, Granite, Iron, Limestone, Manganese, Phosphate, Quartzite, and Sand.

The main challenge in this endeavor was identifying a reliable dependent variable. To address this challenge, we turned to MapBiomas data (2023) as an innovative solution. The MapBiomas Project is a multi-institutional collaboration that maps and analyzes land use changes in Brazil, using satellite imagery to monitor environmental transformations like deforestation and urbanization. It aims to support better environmental management and policy-making by providing annually updated, open-access data on Brazil's land cover changes. Unfortunately, although a promising unbiased source, MapBiomas data (2023) still underestimates mining activities in the Caatinga biome, which led us to further refine our data collection and analysis methods.

To solve the issue of the lack of mining-related data, a proxy was created using MapBiomas Collection 7 (MapBiomas, 2023), focusing on 30 selected land-use transitions resembling mineral explorations from 2010 to 2020. This approach concentrated on aggregating to all transitions to mining, changes within the Caatinga biome that corresponded to a transformation from a “healthy green” pixel to a non-vegetated area or rocky outcrop. The resultant area, significantly larger than initial estimates (5,539% bigger), accounts for approximately 0.7% of the region.

To classify mining activities, transitions to non-vegetated soil (TNVS) within mining tenements without proper permissions were deemed illegal while the same transitions inside mining tenements with clearance to explore were deemed legal. To control for weather effects, TNVS outside mining tenements were included in the model.

Spatial summarization of these data sets over the eleven-years period (2010-2020) provided a detailed view of the total area impacted by both legal and illegal mining activities in the study area, which was aided by a comprehensive set of independent variables categorized into governance, target, place and control, aligned with the theoretical framework.

In the initial stage of this research, an Exploratory Regression served to assess the viability of the planned combination of explanatory variables. However, an issue of non-normality in the residuals significantly undermined the validity of model generated using Ordinary Least Squares (OLS) regression. While spatial lag controls and weights matrices were effective in addressing spatial autocorrelation, as confirmed by non-significant Global Moran's I values, these techniques were not designed to manage the issue of non-linear relationships. Therefore, the shift to Generalized Linear Models (GLM) became imperative, as they offered the analytical flexibility to model non-linear relationships and accommodate various distributional forms for residuals, providing a more robust and reliable analytical framework.

3 RESULTS AND DISCUSSIONS

3.1 EVALUATION OF GOVERNANCE MECHANISMS IN DETERRING ILLEGAL MINING ACTIVITIES

The first hypothesis (H1) posited that effective governance mechanisms, including law enforcement activities, would serve as significant deterrents to illegal mining, which was not substantiated by the empirical data. Drawing upon extant literature that underscores the role of a capable guardian in the deterrence of criminal activities, this hypothesis aimed to scrutinize the potency of governance structures in mitigating mining-related crimes.

However, the empirical evaluation of this hypothesis revealed the real scenario. Model 3, which exhibited a plateau in its explanatory power as evidenced by stabilized R^2 and AIC values, demonstrated that the introduction of variables representing various governance mechanisms did not significantly alter these metrics. This is indicative of the ineffectiveness of such mechanisms, a conclusion further substantiated by the lack of statistical significance in the coefficients corresponding to variables such as fines and police investigations.

This failure of governance mechanisms in deterring illegal mining activities stands in stark contrast to traditional criminological theories that emphasize the importance of a capable guardian. For instance, the Routine Activity Theory, which often serves as a theoretical underpinning for environmental criminology, would suggest that effective governance should inhibit illegal activities by increasing the perceived risk and potential costs for would-be offenders.

The empirical evidence generated by the Generalized Linear Regression models suggests a systemic failure of governance mechanisms, a finding that deviates from the theoretical expectations set forth by criminological paradigms such as the Routine Activity Theory. As elucidated by Model 5, which was rigorously verified against eight alternative models featuring diverse variables and spatial lags, Federal Police investigations in the domain of mining (*nl_pf_mean_mining_r*) were statistically insignificant. Likewise, composite variables accounting for the sum of environmental investigations (*nl_pf_sum*) and the subsequent quantification of environmental damage (*nl_pf_sum_value_ca*) also failed to yield significant results.

In addition, administrative infractions and fines imposed by the ANM, represented by variables *nl_anm_mean_aau* and *nl_anm_mean_afs*, as well as their aggregate measure, *nl_anm_mean_fines*, demonstrated no substantial impact on deterring illegal mining activities, even when tested in various combinations across 11 models.

Finally, the work of IBAMA proved to have the most promising of deterrence effects. Although the average number of fines resulted in consistent insignificance across 9 models, the value associated to the assets that were confiscated by the occasion of interdictions had an impact on reducing 1% of illegal mining where it was done. Despite minimum, the effect was the only statistically significant among deterrence mechanisms.

On a bigger scale, the municipality relative distance to the average national GDP, represented by the variable *nl_mean_r dai*, was always significant, albeit also in a small scale. Like IBAMA interdictions, a unit increase in such a proxy for legal income opportunity reduced illegal mining in 1%, which represents evidence for investing in socioeconomic improvement of the communities inside Caatinga as a prevention strategy for illegal mining.

Finally, hypothesis 1.1 received partial empirical support, indicating that the length of the mining permit process does exert some influence on the incidence of illegal mining activities. However, the marginal effect size and the inversion of the sign across models warrant a more nuanced interpretation. These findings suggest that the relationship between the duration of the mining process and illegal mining is complex and likely subject to conditional factors not encapsulated in the current model. Consequently, further empirical scrutiny would be necessary to fully evaluate the intricacies of this relationship.

In summary, the results indicate a pressing need for a reevaluation of current governance mechanisms, given their apparent failure to act as effective deterrents against illegal mining activities. This finding is not merely an empirical anomaly but an issue that necessitates a substantive rethinking of governance strategies and frameworks in the realm of environmental criminology.

3.2 EVALUATION OF TARGET SUITABILITY

The second hypothesis (H2) posited that the suitability of the mineral itself as a target for criminals, represented by the variable *nl_mean_mri*, would influence the incidence of illegal mining activities. This hypothesis drew on the precepts of Rational Choice Theory, which focus on the cost-benefit analysis, and Routine Activity Theory, which posits that the presence of a suitable target is one of the fundamental pillars that precipitate criminal activities.

The empirical evaluation of this hypothesis lends unequivocal support to its premises. Across the 22 tested models, target suitability exhibited statistical significance, substantiating its role as a potent determinant in the incidence of illegal mining activities. Importantly, the coefficient associated with *nl_mean_mri* remained stable across the models, thereby reinforcing its robustness as an influential factor. This consistency in the models attests to the variable's persistent relevance, even when controls and additional variables are absent (despite skewing results).

The explanatory power of the VALUED approach was somewhat diluted when aggregated among 10 different substances, 11 years and 10km², but its constancy suggests that illegal mining activities are indeed influenced by the minerals available in a given area, a proposition that aligns well with the theoretical foundations of environmental criminology. The VALUED approach effectively served as a proxy for assessing the attractiveness of a target, thereby validating the notion that its suitability is a key determinant in the occurrence of illegal mining activities. The evidence implies that mitigating the attractiveness of these targets, rendering illegal mining more difficult or less profitable, could be an effective avenue for policy intervention.

3.3 EVALUATION OF PLACE SUITABILITY

To address Hypothesis 3 (H3) and its sub-hypothesis (H3.1), the Generalized Linear Regression models incorporated a set of variables representing the geographical and infrastructural attributes of mining tenements. These variables, collectively categorized under Place Aspects, include the area of legal mining (*nl_leg_mean*) and urban areas (*nl_urban_mean*), the total length of roads (*nl_roads_km*), and the number of CPRM mining

occurrences (*nl_cprm_poi_mean*) and gas stations (*nl_gas*). The analytical results are encapsulated in Table 2.

Hypothesis 3 theorized a positive correlation between the geographical and infrastructural attributes of mining tenements and the frequency of illegal mining activities. This hypothesis is substantially corroborated by the empirical results, albeit with some caveats.

Variables representing infrastructure, such as gas stations and urban areas, were insignificant, with the exception of roads, which consistently showed statistical significance, albeit with a low impact. Mineral occurrences were also not important to illegal mining. However, legal mining was consistently the most important driver of illegal mining across all models. Hence, the sub-hypothesis H3.1, which posited that the presence of legal mining activities serves as a criminogenic catalyst for illegal mining, is accepted. The consistency of this variable across the models suggests that legally authorized mining activities indeed potentiate illegal mining by providing the necessary access to market, infrastructure and human capital.

In summary, the empirical analysis lends considerable support to Hypothesis 3 and its sub-hypothesis. While some spatial variables did not achieve statistical significance, the consistent significance of key variables like *nl_leg_mean* and *nl_roads_km* reaffirms the criminogenic role of geographical and infrastructural attributes in illegal mining activities. These findings not only validate the theoretical underpinnings of the Becker-Ehrlich model but also expand its application by incorporating spatial determinants, thereby enriching our understanding in the field of environmental criminology.

4 CONCLUSIONS

This research reveals the complex interplay of governance, target, and place-related factors driving illegal mining in the Brazilian Caatinga. The inefficiencies in current governance align with broader academic concerns about the limitations of global governance in curbing environmental degradation, particularly in mineral extraction. A likely explanation for this contradiction is the inadequate enforcement of penalties, whether through imprisonment or fines. Despite its strengths, the risk assessment model introduced in this study is an initial step in critically evaluating these governance structures.

The empirical rigor applied to scrutinize the effectiveness of governance mechanisms provides a clear picture of their deterrent capacities. In stark contrast to the tenets of environmental criminology, which accentuate the role of a capable guardianship, the governance systems in place in the Brazilian Caatinga are visibly failing to deter illegal mining activities. This systemic failure must not be seen as an empirical anomaly but a substantive lacuna that urgently calls for a complete review and update of current deterrence instruments.

In this vein of thought, the insights gleaned from Becker's economic theory of criminal behavior can be directly applied to understand the rising trend in mining-related crimes in Brazil, particularly in the context of ineffective deterrence. The theory elucidates that criminal actions are the outcome of rational calculations, where potential offenders weigh the benefits against the risks. In scenarios where the deterrence mechanisms — such as the likelihood of being caught and the severity of punishment — are perceived as weak or ineffective, the scale tips in favor of committing the crime. This lack of effective deterrence results in a higher perceived probability of success and lower risk of punitive consequences, thereby encouraging criminal activities.

Therefore, the Brazilian surge in mining-related crimes could arguably be attributed to this imbalance in the risk-reward calculus. When individuals involved in (or considering) illegal mining perceive that the rewards (economic gain, resource acquisition) significantly outweigh the risks (legal repercussions, social condemnation), their propensity to engage in such activities increases. This is particularly relevant in regions where governance and law enforcement mechanisms are either lax or inefficient, exacerbating the issue. The findings of

this study underscore the urgent need for strengthening the deterrence framework — enhancing detection methods, ensuring stricter enforcement of laws, and effectively imposing severe penalties — to realign the risk-reward ratio against the perpetration of mining-related crimes.

This research highlights the synergy between economic concepts and environmental criminology, emphasizing the need for governance models that integrate diverse perspectives, aligned with democracy, transparency, and public participation. It serves as a reference for future studies on deterring environmental crimes using a holistic framework. In Brazil, while law enforcement is mandated, the priority should shift toward evidence-based prevention strategies, ensuring a comprehensive, sustainable, and democratic response to environmental crimes, thus enhancing discourse in environmental criminology and mineral economics. This approach not only aligns with the multifaceted nature of the issue at hand but also ensures a more comprehensive, sustainable, and democratic response to environmental crimes, thereby enriching the discourse in environmental criminology and mineral economics.

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