Proceeding Paper

Tool to Generate Deforestation and Illegal Mining Alerts with Remote Sensing †

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† Presented at the IV Conference on Geomatics Engineering, Madrid, Spain, 6–7 July 2023.
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Abstract: The Colombian environmental policies in the 2022–2026 Development Plan align with international guidelines such as the Escazú Agreement, the Rio Declaration, and the Sustainable Development Goals. In concordance with these ongoing efforts, a specialized tool has been developed to effectively identify potential cases of deforestation and illegal mining linked to forest cover loss and the presence of mercury-contaminated water bodies using planet imagery. The workflow used the ArcGIS Pro Task module, with geo-processes integrated into the Python library, arcpy, and fundamental concepts of object-based image analysis (OBIA) and pixel-based analysis. A methodology known as tip and cue was also implemented to detect illegal mining zones. The tool provides efficient means to study environmental crimes and prevent ecosystem damages.

Keywords: remote sensing; illegal mining; deforestation; ArcGIS Pro tool; planet

1. Introduction

One of the pillars of the National Development Plan 2022–2026 is "Internationalization, Productive Transformation for Life, and Climate Action," which stipulates that the country's socio-economic development and environmental sustainability can no longer be treated as separate processes. Therefore, the government must address the interconnected global crises of climate change, biodiversity loss, and the decline of ecosystem services. In Colombia, an area equivalent to the size of the Risaralda department is lost due to deforestation every two years, impacting biodiversity and services such as water protection and oxygen production. This problem is concentrated in nine deforestation hotspots [1]. Furthermore, it is a matter of concern that approximately 28% of the country's land is affected by illegal mining activities, highlighting a significant challenge in governance and state surveillance [2]. These issues pose a serious threat to the effective functioning of the state and call for immediate attention.

The National Development Plan 2022–2026 is aligned with the Sustainable Development Goals (SDGs) adopted by the United Nations in 2015, which represent the most ambitious global agenda approved by the international community to mobilize collective action towards common goals. The SDGs integrate and balance the three essential dimensions of sustainable development, economic, social, and environmental, providing a valuable roadmap for articulating the formulation of global policies [3]. Without a doubt, a clean, stable, and predictable water supply stands as one of the utmost invaluable ecosystem services that forests bestow upon humanity [4], but throughout the course of human civilization, the Earth has experienced a significant decline in forested areas, shrinking from approximately 60 million square kilometers to less than 40 [5]. In Latin America, deforestation occurs mainly in areas dedicated to drug cultivation and distribution [6]. Colombian forests and jungles face a high risk because criminal groups have stopped relying solely on drug

trafficking, as they have found more economic benefits in developing other environmental crimes such as illegal logging, illegal mining, and wildlife trafficking [7]. Politically, the peace agreement signed in 2016 identifies Colombian ecosystems as direct and indirect victims of the armed conflict. Illegal mining has devastated entire ecosystems, increasing violence and war, displacing farmers to urban areas, and causing loss of biodiversity [2].

Platforms such as Global Forest Watch and Map Biomass Alert provide forest and jungle monitoring to focus on areas with biomass loss, so that governmental agencies can make decisions and take action against deforestation and other environmental crimes associated with it.

This article proposes a methodology to identify deforestation and illegal mining based on satellite images from the Planet Scope constellation. A tool was developed to detect mercury-contaminated bodies of water and deforestation in the Cauca River in Colombia using object and pixel-based analysis applied to satellite images. The workflow also employs the tip and cue technique, combining machine learning methods and tonality extraction. The tool's results yield two geographic layers that delimit the study phenomena. The methodology demonstrates efficiency in studying environmental crimes and their change over time and is recommended for use in processes aimed at detecting, mitigating, and preventing damage to the ecosystem.

2. Materials and Methods

2.1. Preliminary Evaluation of the Study Area

The study area is located on the banks of the Cauca River and includes the townships of Margento, Palomar, Palanca, and the hamlet of Villa del Socorro in Caucasia, Antioquia. Despite becoming an economic center due to its connection between departments and the gold rush, illegal armed groups have caused harm through illegal mining, which has negatively impacted both the ecosystem and the inhabitants of the municipality [8].

2.2. Data Acquisition and Characterization of the Phenomenon

The used imagery is from Planet Scope, these satellite images have 8 spectral bands and 3 meters of spatial resolution, provide a spectral range of 431 nm to 885 nm, and enable daily monitoring of land cover phenomena. Mercury, a pollutant that poses health risks to humans and the environment, is used in gold mining to extract the metal from rocks. The heating process to separate mercury from gold can contaminate soils and rivers [9]. In optical sensors, mercury appears as a cyan-blue tone in natural color satellite images, and the 864 (RGB) color combination best highlights it, allowing for easy differentiation from vegetation (red color) and bare soil or structures (white color) and facilitating the identification and delineation of mining pits.

2.3. Cover Classification Methods Validation

Object-based image analysis (OBIA) offers several advantages over pixel-based techniques, including greater precision in coverage classification. OBIA involves segmentation and classification phases to identify significant objects in the image and categorize them into pre-defined classes [10]. Support vector machines (SVMs) are supervised classifiers that have shown excellent results in classification and are commonly used in machine learning. They were chosen for both pixel-based and object-oriented classifications due to their success in previous studies. The workflow presented offers both options to accommodate the expertise and knowledge of the end-user [11].

2.4. Tool Development

The interface was developed using Esri's ArcGIS Pro 2.9 software (Esri: Redlands, CA, USA) purchased under a partner license and the task module, which follows a set of steps within the same workflow. Each section (tip and cue) contains an evaluation module for the interpreter, allowing the user to edit geographic layers based on their knowledge of the area. Results are verified through a confusion matrix that includes the Kappa index for

the presumed deforestation module and an accuracy percentage for the tonality module. Figure 1 displays the interface of the tool [12].
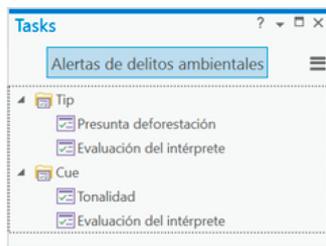
Figure 1. Environmental crime alerts tool interface.

2.4.1. Tip: Deforestation Monitoring

The large-scale analysis was developed to monitor deforestation in forest areas of the area of interest. Two tools have been developed: one using pixel-based classification and the other using object-based classification. Both tools aimed to evaluate and quantify the loss of vegetation cover. The inputs required are pre- and post-event images, segmentation layer, and forest samples (for object-based classification) or a classifier file (for pixel-based classification).

2.4.2. Cue: Extraction of Elements by Tonality

The specific analysis aimed at detecting mercury in illegal mining. Elements of interest were automatically extracted from the satellite image, based on their tone or color. The inputs required satellite imagery and a geographic layer containing samples of mercury, which represent its present in wells. Digital level values were extracted and compared throughout the study area to identify other areas where mercury may be present. This approach allowed for the detection of mercury in illegal mining operations.

3. Results

3.1. Tip (Deforestation Detection)

At the end of this phase, four geographic layers are produced, 2 forest classifications which are depicted in Figure 2 and one deforestation layer for each method showed in Figure 3. The first two classification layers identify the current forest cover in the study area, while the other ones represent the forest loss calculated by comparing the coverage between the given dates. These layers can be obtained through either object-oriented (OO) or pixel-by-pixel (PP) classification methods and are stored as vector elements, enabling the calculation of areas of interest and interpreter editing. Object Oriented method provides the best result; hence, it was chosen for further analysis.

(**a**)   (**b**)
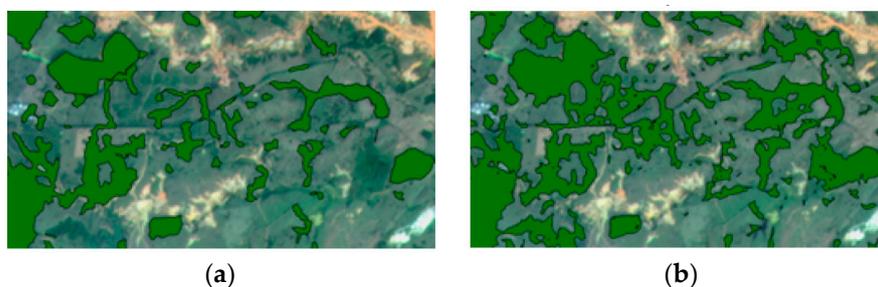
Figure 2. Forest classification. (**a**) Output using OO method. (**b**) Output using PP method.

The total loss of forest cover for the study area was estimated at 218.1 ha for the OO method of 5685 ha (3.83%) and 234.1 ha for the PP method of 6340 ha (3.69%) before the intervention of an analyst. In this case, the object-oriented classification method is superior in ac-

curately classifying forest cover and determining its loss, as seen in Figure 4. The confusion matrix for this method demonstrated a 99% accuracy, confirming its excellent performance.
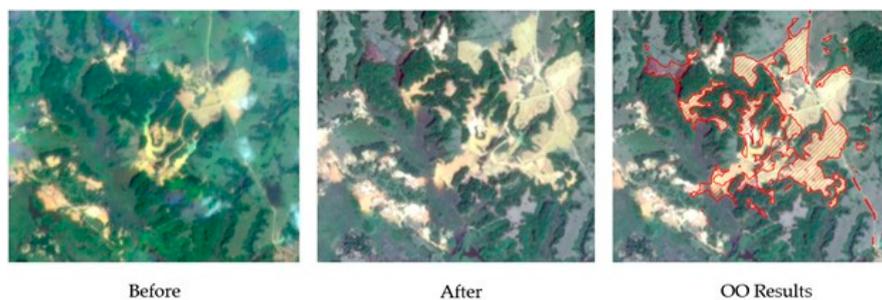
Figure 3. Detection of forest loss in deforested area through OO method.

ClassValue	Bosque	No_bosque	Total	U_Accuracy	Kappa
Bosque	250	10	260	0.961538	0
No_bosque	0	240	240	1	0
Total	250	250	500	0	0
P_Accuracy	1	0.96	0	0.98	0
Kappa	0	0	0	0	0.96

(a)

ClassValue	Bosque	No_bosque	Total	U_Accuracy	Kappa
Bosque	198	0	198	1	0
No_bosque	1	301	302	0.996689	0
Total	199	301	500	0	0
P_Accuracy	0.994975	1	0	0.998	0
Kappa	0	0	0	0	0.995823

(b)

Figure 4. Confusion matrices (**a**) using PP method and (**b**) using OO method.

3.2. Cue (Illegal Mining)

The tonal extraction process is executed after detecting the areas with forest cover loss. It results in two geographic layers, one vector and one raster, which delimit the mercury-contaminated bodies of water. The polygonal layer is useful for calculating coverage area metrics, while the raster layer can be processed with other images and indexes. The results confirm the existence of several contaminated wells and highlight the contaminated segment of the Cauca River, which puts nearby settlements at risk (Figure 5).

Figure 5. Geographical layer with the areas of the study area contaminated by mercury.

4. Discussion

This case study demonstrates how image processing and tip and cue concept can contribute to the early detection of environmental crimes, aligning with Colombia's Sustainable Development Goals and National Development Plan 2022–2026. The presented tools generate valuable products for analyzing deforestation and mercury contamination in a territory that is interoperable with other geographic formats and fully editable. However, field verification is recommended as errors may occur due to radiometry, haze, or shadow, and the results need to be adjusted and validated by an analyst. The study area has an estimated 5700 hectares of forest, with 220 hectares lost between January 2021 and January 2022, representing a 4% loss. The main issue in the region appears to be illegal mining,

with tonality coverages identifying 8 km² of mercury contamination, including the Cauca River stretch. The analysis suggests a relation between mining and the formation of new water wells in deforested areas.

In conclusion, the integration with Esri's Task module allows for an intuitive and easy-to-use interface, while maintaining accuracy in processing, making the tools presented in this study accessible to a wide range of users and fields, regardless of the user's level of knowledge in remote sensing and information systems. However, for future research, the implementation of this workflow in other development environments should not be ruled out.

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