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ENVIRONMENTAL MONITORING WITH SATELLITE IMAGES: AN APPROACH BASED ON THE ENVIRONMENTAL RECOVERY OF A MINING PROJECT IN URUGUAY

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Abstract: Evaluating changes in land cover in areas affected by mining activities is essential to understand their impact on the environment and carry out environmental remediation processes. This work presents an analysis of the area affected by mining activity and its subsequent recovery, during the exploitation of the San Gregorio gold project, Uruguay, using Landsat 5TM and Landsat 8 OLI image processing techniques, with the free software QGIS. The methodology implemented consisted of the preprocessing of Landsat images, application of RGB combinations, semi-automatic classification, calculation of the vegetation index and classification of areas.

The changes produced in land cover were identified in periods of up to 5 years, from the start of operations in 1996 to the closure of activities in 2019. For each period, the images were visually interpreted in false colors, a supervised classification was processed and The normalized vegetation index was analyzed, generating coverage maps of the areas affected by mining activities, as well as determining the spectral signatures of these coverages. The results show the damaged areas and the areas recovered during the mining project and how the vegetation, soil and water evolved over time, reflecting the changes produced. The use of satellite images is an excellent tool for environmental monitoring of mining activities, helping to understand the environmental recovery processes and the future territorial planning of the area.

Keywords: supervised classification, coverage maps, mining activity.

INTRODUCTION

In recent decades, the classification of land cover in areas of mining operations has become very important to understand the influence of these activities on the regional geoenvironment and for the procedure of how

to evaluate their environmental impact (Chen, W. et al, 2018). Currently, technologies such as remote sensing and GIS studies are widely used and effective in identifying the spectral profile and making decisions on corrective measures and remediation of environmental impacts. The application of RGB, infrared and NDVI color index techniques has been successfully used in mining waste research (Wajs, 2018). The visual analysis of the image incorporates complex criteria, such as texture, structure, location or arrangement, which allow discriminating categories with a uniform spectral behavior that can be adequately separated, while the digital treatment is based on the radiometric intensity of each pixel, which can be very similar in different coverages (Chuvieco, 2010). Once the false color satellite image is obtained, the first and most important activity is the visual interpretation of this image. Lira (2010) states that the recognition of an object in images implies its classification. This task involves visually examining the reflectance levels of objects, recognizing and identifying them by their shape, color, size and other properties, such as a specific geographical location, if there is local knowledge of the area.

In Uruguay there is little history of research with satellite images, some of which refer to geological-mining studies, such as the application of Aster images, to detect mineral alterations in the eastern sector of the Nico Pérez Terrain (Ferrizo, 2016 ; Ferrizo and Abre, 2016). Or the work of Ferrizo and Abre (2019), where they carry out structural interpretations on Isla Cristalina de Rivera (ICR) with Landsat 7 ETM images.

Considering that vegetation and soil are indicators of environmental quality, the main objective of this work is to quantify the area degraded by mining activity and the revegetated areas, through maps of vegetation cover, soil and water in the San mining district.

Gregorio, in the period 1996-2020. This type of research is unprecedented in Uruguay, which is why it provides relevant information on the environmental monitoring of these and other activities that involve the industrialization of natural resources. The interpretation of satellite image data allows us to identify areas of removed soil, revegetated or recovered soil, quality of vegetation and water, developing a spatio-temporal methodology of activities and analysis of anthropic changes in the mining district, supported with Google Earth images. images from the Uruguayan Spatial Data Infrastructure (IDEuy) viewer and calculation of the Normalized Differential Vegetation Index. With the results of this research on the ground, it is possible to compare and see its evolution over the years, as well as report the percentages of affected and recovered areas, generating important information for future geoenvironmental studies. The specific objectives are to obtain the spectral characteristics of the different components of the surface, and to determine the reference spectral curves of the main coatings present. Currently, technologies such as remote sensing and GIS studies are widely used and effective in identifying the spatial footprint and supporting decisions on corrective measures and remediation of environmental impacts. Finally, obtain a georeferenced database through Geographic Information Systems, to be used in other research, to help plan how the territory is affected in the development of mining projects in Uruguay.

STUDY AREA

The study area covers approximately 12 km², including the San Gregorio gold district, located 5 km south of the Villa Minas de Corrales, Rivera department, in the northern part of Uruguay.



Figure 1: Left, map of Uruguay with location of the study area (red box). Right, Google Earth image where the mining works and Minas de Corrales town can be seen.

The San Gregorio gold deposits are mesothermal mineralizations in a shear zone. They are located on the Isla Cristalina de Rivera (ICR), within Terra Nico Pérez (Bossi and Gaucher, 2014). The rocks present are gneisses and basic rocks in granulite and metasediment facies, including banded iron formations, of Paleoproterozoic age. The structural control of gold mineralization is a NW-SE direction shear system, affected by E-W faults, which control mineralization (Ferrizo and Abre, 2019).

The most relevant natural aspects of the area are listed below, as an argument to understand the natural evolution of the affected areas. The predominant climate is temperate, with rain every month of the year. The average annual rainfall is 1,300 mm, with a monthly average of 110 mm. The average temperature is 18°C, with a maximum of 25°C in January and a minimum of 7°C in July. The relative humidity

of the air is 71% in the region, according to data from the Uruguayan Institute of Meteorology (www.inumet.gub.uy).

The physiography of the terrain corresponds to small undulations and hills with heights that do not exceed 230 m. Towards the south of the study site there are large areas of sedimentary plains.

The soil in the highest topographic parts is very scarce, alternating between rocky outcrops and grayish-brown sandy soils, with a depth of 10 cm. On the slopes and lowlands it reaches 40 cm deep, with a predominance of black soils. Land use is limited to grazing sheep and cattle. The predominant soils are caused by natural pedogenetic processes, with a sandy, clayey and stony texture. The slopes of the land are of the order of 5 to 20%. The vegetation is predominantly summer grassland, sometimes with scrub, generally associated with streams and low areas. In the field or natural meadow there is little vegetation, with a predominance of grasses and low, medium-sized vegetation such as *chirca*, *carqueja* and *cardilla*.

The hydrography of the area is made up of the Corrales stream, which separates the mining areas of San Gregorio and Arenal, and in the rest of the property there are small streams, with low flow but in a permanent regime. To the south of the area there are some artificial dams, which accumulate water for rice irrigation.

The San Gregorio mining area has had several phases of open pit mining since 1995, increasing its operational activity as satellite deposits were discovered and production increased. Therefore, areas affected by development vary in their location, or sometimes appear in the same places due to the expansion of the mining pit. In recent years, exploitation has been carried out through underground mining, both in the Arenal Mine and in the San Gregorio Mine.

METHODOLOGY

The images were downloaded from the United States Geological Survey (USGS, <http://earthexplorer.usgs.gov/>) website, which were reviewed and classified according to the date and the percentage of cloud cover covering the image.

The following table shows the dates and acquisition data of these images:

YEAR	DATE	Sensor LANDSAT
1996	02/01/1996	5 TM
2000	11/10/2000	5 TM
2005	26/11/2005	5 TM
2010	08/11/2010	5 TM
2015	06/11/2015	8 OLI
2019	17/11/2019	8 OLI

Table 1: Date data of the treated images.

The criterion for selecting Landsat 5 images was their quality and low cloud cover. Most of the Landsat 7 images for this area have the problem of continuous scratching, so many images had to be searched carefully and discarded. Landsat 5 and 8 OLI images were selected, in the WGS84 reference system, and with similar date ranges, generally within the month of November, with the exception of 1996, to identify the development of vegetation in the same periods (see Table 2). After observing the USGS database, it was decided to choose, for each period, the images from the month of November, except for the year 1996. The choice is related to the knowledge of the climate in the southern hemisphere, where the The season is spring and the vegetation is healthy and vigorous, and the soils are not so saturated with water, causing better discrimination of the land cover. Since the rains are not so intense, they do not affect the disproportionate drag of solid particles into the water, making them more cloudy.

The previous investigation included the review of precipitation rates, which according to the historical record of the Agricultural Research Institute (INIA) portal, the accumulated amount for the month of November in the years 2005, 2010, 2015 and 2019, was an average of 80 mm. of rain, a behavior slightly lower than the typical average for those dates (www.inia.uy/gras/Clima/Precipitaci3n nacional/Mapas de precipitaci3n acumulada).

To carry out the geoprocessing of the information contained in the satellite images, the free software Qgis (Manual Qgis 3.10.; www.qgis.org) and the SCP (Semi-Automatic Classification Plugin) plugin were used.

The following flowchart presents the stages used for the multi-temporal analysis of the images.

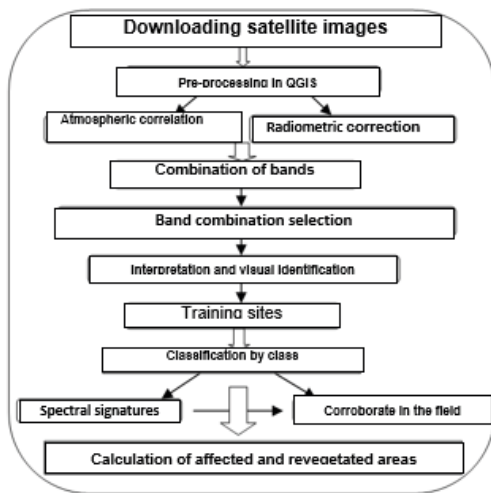


Figure 2: Flowchart of methodology used.

The SCP plugin provides the tools for pre-processing remote sensing images, such as atmospheric correction, radiance to reflectance conversion, image combination, raster calculator, among others (Congedo, L., 2018). The study used bands that cover the visible, near infrared (NIR) and shortwave infrared (SWIR) spectral range (see table 2). Band combination tests were carried out, opting for image compositions RGB 543 for

Landsat 5 and RGB 654 for Landsat 8. The areas affected by mining exploitation are very recognizable in these bands of the Landsat sensor, because the reflectance spectra of mining waste are sufficiently different to allow separation from other uses and land covers of adjacent regions. Combination 543 in Landsat 5, in addition to vegetation, shows greater differentiation between soil and water. The Landsat 8 combination 654 is conducive to vegetation analysis. The characteristics of these bands for the different sensors are that they are similar in wavelengths and the same pixel size, according to the following table.

The visual interpretation process began with the recognition of the areas of mines, dumps, tailings dam, infrastructure, and revegetated areas, based on the observation of historical and current Google Earth images. The viewer of the Spatial Data Infrastructure Institute of Uruguay (IDE) was also used, which has free access to the geographical information of the territory (https://visualizador.ide.uy/ideuy/core/load_public_project/ideuy). On this page the images have very good definition and sharpness and there is also an infrared image treatment, which effectively discriminates the vegetation, so the terrain texture can be separated with excellent accuracy. Figure 3 compares images from these two servers, obtaining good discrimination and coincidences in soil, vegetation and water cover.

LANDSAT 5			LANDSAT 8OLI		
BAND	BROAD (μm)	RESOLUTION (m)	BAND	ANCHO (μm)	RESOLUTION (m)
Band3 Red	0.63 – 0.69	30	Band4 Red	0.64 – 0.67	30
Band4 NIR	0.77 – 0.90	30	Band5 NIR	0.85 – 0.88	30
Band5 SWIR1	1.55 – 1.75	30	Band6 SWIR1	1.57 – 1.65	30

Table 2: characteristics of the bands used.



Figure 3: Google Earth image from March 2019 versus IDEUy viewer image from February 2020.

On the other hand, and to help the selection of representative areas, it was complemented with the calculation of the Normalized Differential Vegetation Index (NDVI), in order to separate areas of bare soil from soils with vegetation. Water, due to its greater reflectance in the infrared than in the red, has negative values. Bare soil or soil with very little vegetation, or bare rocky areas, have values close to zero. Negative values represent surfaces without vegetation. While healthy vegetation presents the highest NDVI values. For example, in Figure 5, images from 1996 are compared to those from 2019, showing in the latter image that the removed soil has

values below or close to zero, indicating that the vegetation is practically non-existent or there is bare soil.

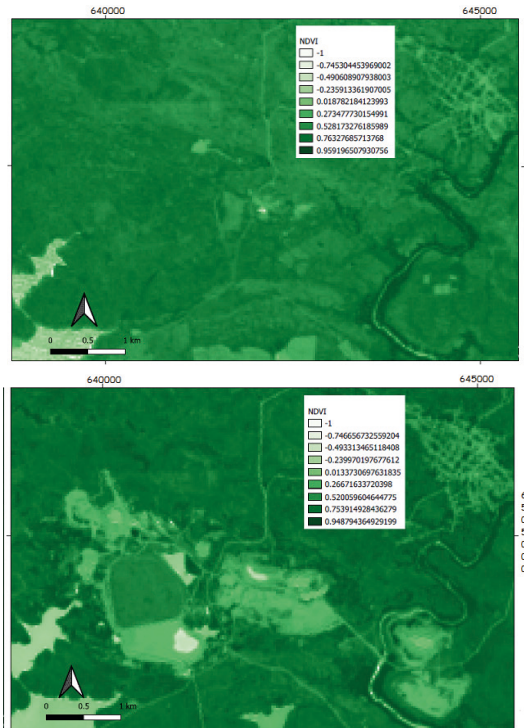


Figure 4: on the left NDVI of 1996 and on the right NDVI of 2019.

Once these processes were formed, the visual interpretation and analysis of vegetation began, in the combination of RGB bands 543 for Landsat 5 and in the combination 654 for Landsat 8. Mining areas with soil movement and waste collections, present irregular shapes, with light colors, between blue and pink with slight magenta tones, due to the high reflectance of these materials; sky blue color for waters with sediments; black for clean waters and the vegetation is shown in various shades of green and pink, which

vary depending on the type and location conditions, highlighting the areas with native forest in a fluorescent green tone (Figure 6).

according to the criteria previously described, it was decided to create a legend with seven types of cover, divided between soils, type of vegetation and water, which are shown in the following table:

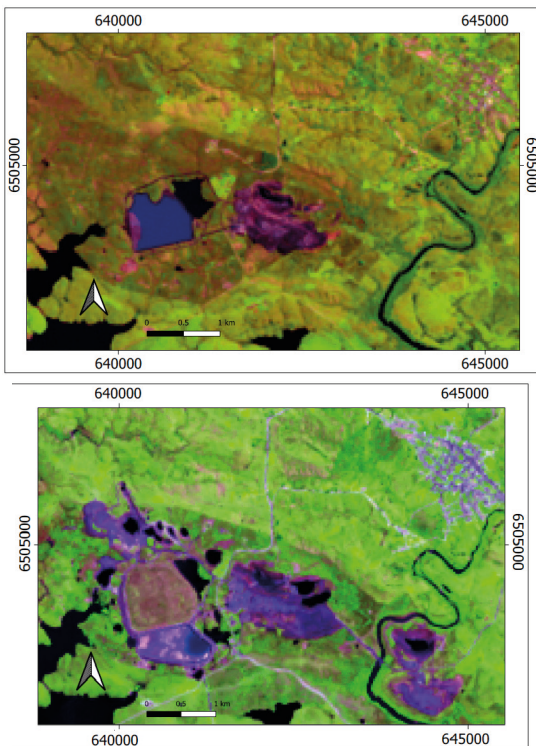


Figure 5: On the left RGB 543 image from 1996 and on the right RGB 654 image for 2019.

Subsequently, training areas or Shapefile were generated, recorded on the RGB color composition, from the visual interpretation of the satellite images, the observations of the Google Earth images and the IDEuy images, creating regions of interest or ROIs. manually and digitizing polygons with pixels belonging to the same land cover class. This classification technique is based on grouping pixels that have similar regions of the spectrum, and that are associated with different coverage classes. So that the evaluation was representative for each class, on average, sampling was carried out with six polygons for each one. The sample size was also considered, to generate uniform sampling. These polygons are named according to a macroclass identification (MC ID) and a class identification (C ID), according to the Qgis Manual 3.10. Next, and

CLASS	DESCRIPTION
Removed soils	It is land affected by mining activities, infrastructure or preparation of land for work.
Revegetated soils	It is soil that has already been restored, with continuous vegetation growth.
Clean water	They are reservoirs or water courses, which do not present significant detrital contributions or with little contamination of sediments.
Water with sediment	is water that is contaminated by suspended sediment, as in the case of tailings dams or an abandoned mine
Low vegetation	It is the vegetation composed of grasses typical of the natural landscape.
Dense vegetation	formed by chirca thickets and mountainous mountains
Natural mountains	It is an association of tree species that develop naturally along streams.

Table 3: Classification and description of classes.

Before the final classification raster, editing and changing colors was carried out for each of the classes, maintaining the same criteria for the entire study period, in addition to a field visit, to corroborate these areas.

The field visit was carried out in November 2019, to verify if the selected regions of interest (ROI) corresponded to the seven defined coverage classes. With the support of employees of the mining company and with the use of GPS, I visited the previously selected areas, representative of each coverage. Different places were visited, such as dumps, mines, roads and restored areas, observing the corresponding vegetation, land use and water.

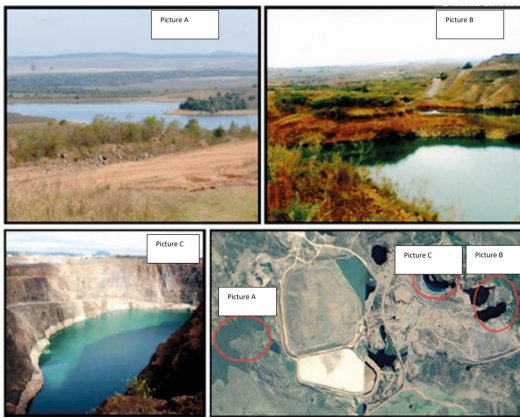


Figure 6: Photographs taken during the field survey. In photo A you can see a pond with clean water and vegetation. In photo B you can see part of the open pits full of water and vegetation typical of the place. Photo B is the San Gregorio mine partially covered with water. On the right below is the location of these photos at the mine site.

The last stage of the research was the generation and interpretation of the spectral angle (SAM) in the visible region, for all the classes studied and corroborated in the field. Once these spectral fingerprints were obtained, they were compared with the available spectral libraries, generating conclusions according to the mapped surfaces.

RESULTS AND DISCUSSION

The supervised classification technique accurately defined all mining activity sites and revegetated sites, allowing their representation in coverage maps, as shown in Figure 6.

It is observed that in the surroundings of the mining activity the soils were not affected, except for very specific points, so the environmental impact in question is minimal.

To compare the impact on soils and vegetation, in relation to the restored areas, the area shown in Figure 8 was delimited, where the main mining operations and their impacts on the surrounding environment are located, according to the coverage map for the year 2019. This area delimits the entire area

covered by the San Gregorio mining project.

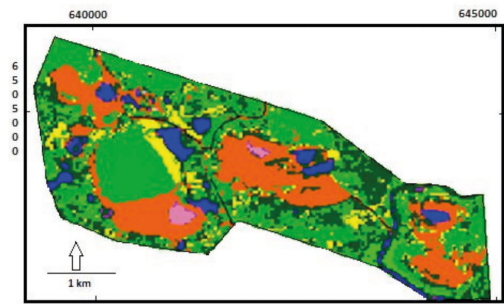


Figure 8: Delimitation of the area taken to compare affected soils versus revegetated soils.

From the classes of removed soils and revegetated soils, the area of each of these classes and their accumulation over time was calculated with the Field Calculator of the QGIS software, generating the following table.

From the analysis of the table, it is observed that of the total of 492.42 hectares affected by the mining project during 24 years, only 172.22 hectares were restored. That is to say, only 37.17% of the area affected by mining operations was restored. The largest land restoration was carried out in the last 10 years, being the period 2015-2019, where the largest area was restored, with 116.47%.

This same data is then displayed in graphs.

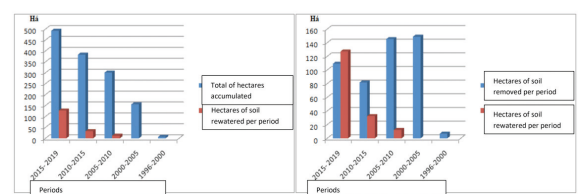


Figure 9: Graphs showing, on the left, the total occupied areas & hectares of revegetated soils per period. On the right, comparison between hectares removed & revegetated per period studied.

The graph on the left shows how little land was restored during the useful life of the project, while the graph on the right shows significant mining activity between the years 2000 and 2010, and in the last two periods it was where

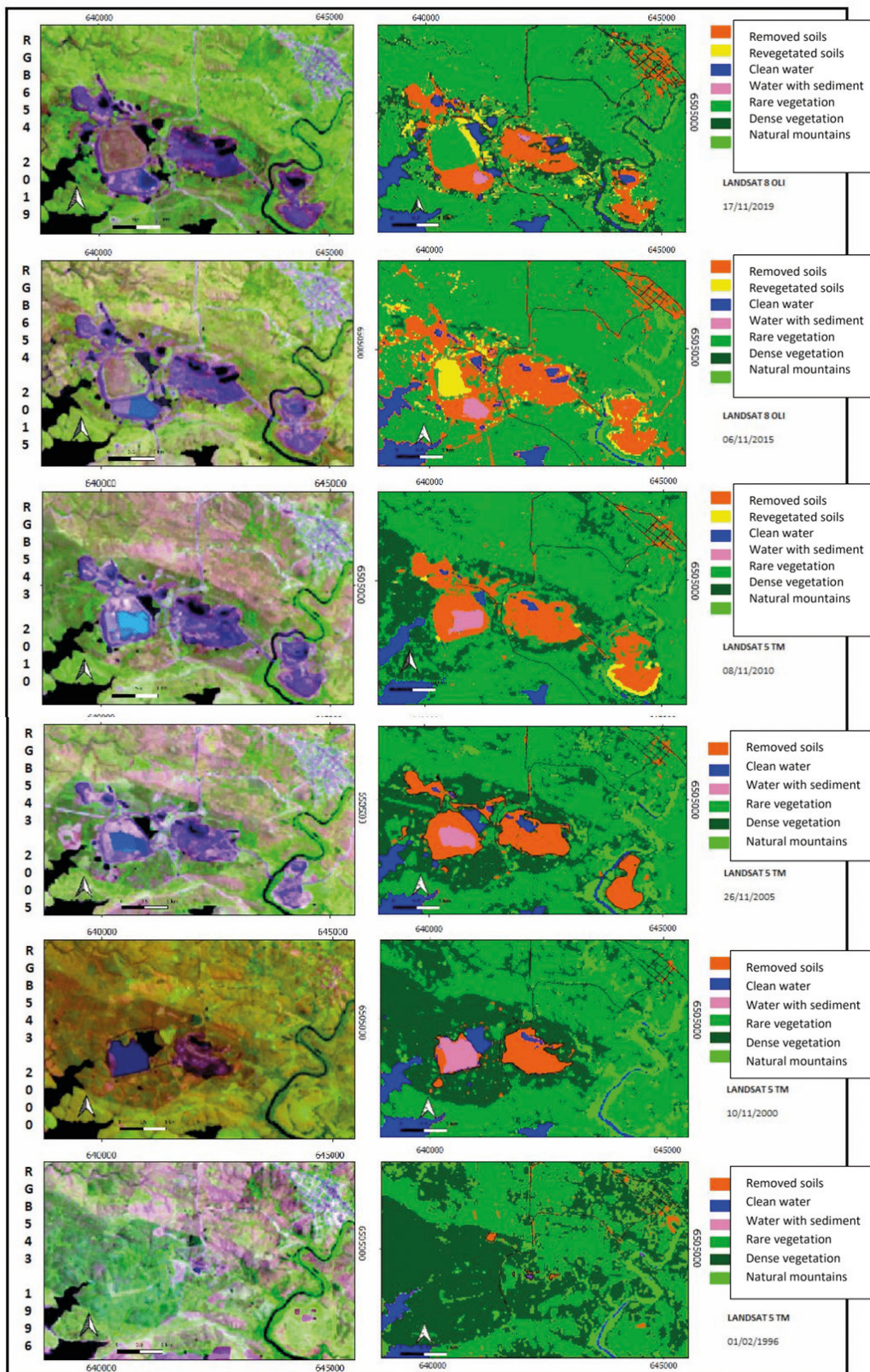


Figure 7: On the left, RGB color composition images and on the right, coverage maps of the mining exploitation area for the years 1996, 2000, 2005, 2010, 2015 and 2019.

Period	Total accumulated occupied hectares	Hectares of soil removed per period	Hectares of soils revegetated for periods	% restored by period	% restored of the total area
2015- 2019	492.42	109.28	127.28	116.47	25.85
2010-2015	383.14	81.91	32.64	39.85	8.52
2005-2010	301.23	145.43	12.3	8.46	2.80
2000-2005	155.8	148.97	-	-	-
1996-2000	6.83	6.83	-	-	-

Table 4: Coverage areas of removed soils and revegetated soils, by year and percentage of restored area by period.

The largest land restoration was carried out. The revegetation works targeted areas with great environmental and visual impact, such as the tailings dam, or waste dump areas with abandonment of exploitation. An example of these environmental restorations is what can be seen in Figure 10, where you can see the restoration of the slope of a waste dump.



Figure 10: Photograph of the view of the slope of the waste pile in Mina Arenal, reconditioned and revegetated, and on the right aerial image of the place, where the growth of vegetation can be seen.

Also in tailings dam 1 (Figure 11), which contains mining waste with cyanide, all surface revegetation was carried out, covering an area of about 80 hectares.



Figure 11: View of the tailings dam, covered and with revegetation on its surface.

Regarding the vegetation and according to the data observed in the satellite images and the environmental reports of the operating mining companies, the initial vegetation of the area was composed of large chirca thickets and typical shrub forest, classified in this work. as dense vegetation. In the first beginnings of the mining project, the environmental impact was minimal, as can be seen in Figure 7 (period 1996 to 2000). Since 2005, there has been a significant deterioration of the vegetation, and this is related to the development of the project, with the opening and entry into production of new mining pits (according to [http://spanish.orosur.ca/ Corporate Profile](http://spanish.orosur.ca/Corporate Profile)).

Starting in 2010, the mining company began to explore and exploit nearby satellite deposits, with a significant deployment of drilling equipment and vehicles. To create access to drilling sites, a network of roads and drilling platforms is developed. Therefore, the vegetation cover of the environment is affected, especially the shrubs.

As the operational advance of the mines spreads, the dense vegetation loses area. Then, a minimum presence of dense vegetation is observed during 2015, the explanation for which is that in that period, there was an important brown field type exploration campaign, so it was necessary to clear the land to carry out the corresponding prospecting work. Already in 2018, activities ceased and the vegetation began its natural recovery.

As for the wells or pits left by mining operations, they are generally filled with water, essentially free of sediment, at least temporarily (Fig. 12). These mining pits, in general, do not have a closure forecast, since the mineral resources at depth are probably not completely exhausted, and may be extracted in the future. It was estimated that these areas occupy a total of 61.6 hectares (Figure 12). If we discard that area, the percentage of revegetated area becomes 40.1% of the total affected.

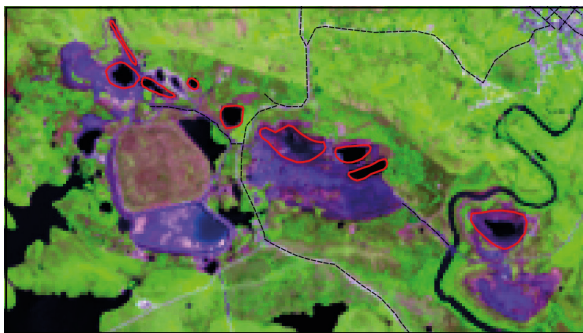


Figure 12: RGB654 image with the outline of the mines.

In general, land restorations focus on giving greater environmental care to the areas of waste piles, infrastructure and tailings dams, which have greater visibility and greater visual impact. In Uruguay, a mine closure or abandonment plan is required by law (Decree 349/2005), with conditioning and recovery of the affected area, which is what the operating company began to carry out in recent years (Figure 7, period 2015- 2019).

Finally, the spectral fingerprints of the classes obtained were studied to corroborate the different surface types. The spectral differences of the components of these areas, in relation to the environment, are important to know the state of the vegetation and the bare soil. The spectral signatures or fingerprints were extracted with the SCP plugin, in the band combinations of the satellite image, for the different types of soil, water and vegetation surfaces involved in this investigation (Table 3). With this software plugin, the spectral signatures are defined in the training areas, and are the set of statistics of central tendency and dispersion (mean, minimum and maximum, standard deviation) of the reflectance, and that in theory define the spectral behavior of related coverage (Congedo, L. 2018). In areas with bare soil, such as mining waste dumps, the reflection depends on the mineralogical composition of the deposited mining waste and the size of the particles, as well as the humidity of the ground and its physical properties due to swelling in some cases, and compaction. In others. When the material is dumped in the dump, a discharge zone is formed defined by a slope specific to the sliding of the material, and therefore sponge zones. On the contrary, when there is circulation of equipment, there is compaction of the soil and dust is generated. This affects the water regime and the development of vegetation. The different levels or embankments, with slopes of varying slope in the dumps, is another factor to consider in the incidence and exposure of energy and therefore reflection. The spectral fingerprint for these materials presents a low reflection, behaving as a line declining towards the red band. In the case of revegetated soils, it resembles dense vegetation. The vegetation has a high reflection in the green channel (0.53-0.59 μ m) and a low reflection in the visible red channel (0.64-0.67 μ m). The rest of

the components present common behaviors for each cover (Figure 13).

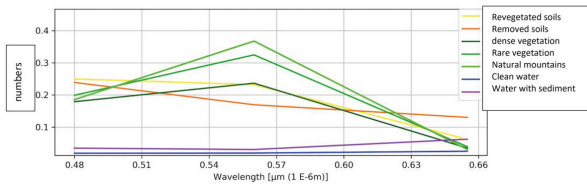


Figure 13: Spectral signature graph extracted from the SCP (2019 images). Note that the vegetation separated into classes (rare, dense vegetation and mountains) have a peak in the green band (0,5613 µm).

CONCLUSIONS

The results obtained in this work, using remote sensing techniques with Landsat images and their treatment with GIS software, were successful and it was possible to estimate the affected areas and revegetated areas in the San Gregorio mining project, from the beginning of the mining operation until recent years.

The supervised classification was accurate in identifying the characteristics of the removed soils and the vegetation affected by the mining works. Once the classification of the different coverages for each image has been obtained, it can be observed that the areas directly affected by mining activity are very well represented. Objectively, the environmentally recomposed areas were inferior compared to the affected areas, but in the same way, it is observed that the planted vegetation is in good condition, or

even confused with the nature that surrounds it.

Dumps or waste piles, which affect huge areas, are easier to restore, because they can be easily worked by smoothing the contour of the surfaces. Very good surface restoration was also achieved in the tailings dams.

Therefore, it is concluded that research with satellite images is a very good tool for controlling areas degraded by mining activities, observing the progress of restoration on the ground and the behavior of vegetation over time.

Data studies and remote sensing techniques have been applied in many places in the world, with the aim of monitoring the environmental impact generated by mining exploitation, but in Uruguay to date, this methodology has not been applied as a mining monitoring tool. -environmental, or for any industry that interacts with the environment, with the objective of planned and sustainable development of the environment.

With this work, results begin to recommend recovery and restoration strategies for the affected surfaces, as well as generate tools to evaluate and promote different alternative uses, both agricultural and tourism, that generate economic benefits for the region.

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