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Remote Sensing for Environmental Monitoring: A Case Study of the Momotombo Geothermal Field, Nicaragua

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ABSTRACT

The environmental impacts of geothermal projects have been widely discussed in countries with great potential for geothermal development. In Nicaragua, all geothermal areas are located within protected areas, therefore, environmental and social impacts must be assessed prior to development and monitoring programs during construction and operation stages must be implemented. The use of land is one of the most common issues when projects are located near towns and villages, a project can cause some social concerns about the real impacts of geothermal development, thus it is important to effectively monitor the change in land use. The Momotombo geothermal field is located within the Momotombo Volcanic Complex Nature Reserve, however, the project was developed before the protected area was created in 1983. The first exploration well in the field was completed in 1974 and the first generation unit of the geothermal power plant was commissioned in 1983 and a second unit in 1989, needing the drilling of additional wells and therefore expanding the area used by the project. The purpose of this paper is to analyse changes in the composition of land use within the Momotombo geothermal concession and its impacts within the protected area during the last 30 years. Satellite images from different sensors such as Sentinel 2A and the historical Landsat Series were analysed for comparing the evolution of the geothermal development and the effects on biodiversity conservation in the protected area. The multitemporal analysis of satellite images shows that land use within the geothermal concession has changed from mainly productive areas (agriculture and livestock) in 1989 to a type of secondary tropical dry forest in more recent years, inferring that environmental management has benefited the recovery of flora species and the ecosystem in the geothermal development area.

1. INTRODUCTION

The Momotombo geothermal field is located in western Nicaragua, in the southern slope of the Momotombo Volcano in the Maribios Range. Geothermal development in Nicaragua started in the year 1966, when no environmental considerations for project management were implemented in the country. The first geothermal unit (35 MW, singleflash) in the Momotombo geothermal field was commissioned in 1983. Six years later in 1989, the second unit (35 MW, single-flash) came into operation.

The Momotombo geothermal concession covers 9 km^2 within the Momotombo Volcanic Complex Protected Area, which total area is 148.44 km^2. The main environmental aspects for the Momotombo geothermal field and power plant were first discussed by BID-OLADE (1993), the key aspects were related to generation of wastewater (geothermal brine and condensate), cooling water demand and non-condensable gases emissions.

In the Momotombo geothermal field 47 wells have been drilled into 2 km^2 area. The Momotombo geothermal field is a good example of field management after improper operation of the field for years, the full operation of the installed capacity of the plant was never reached due to lack of steam. Until 1999, the geothermal system of Momotombo suffered from over-exploitation that induced excessive flashing and intrusion of cold water in the reservoir resulting in a drastic decline of electricity generation and brine was discharged into Lake Xolotlán (Porras, 2008). In 1999, ORMAT took over the concession for 15 years and under its administration four wells were drilled, a 7 MWe bottoming unit installed and full reinjection of waste fluids implemented. In 2013, ORMAT sold its stake to Momotombo Power Company which currently operates the power plant.

The aim of this paper is to discuss the environmental effects related to the development of the Momotombo geothermal field and the commissioning of the first geothermal power plant in Nicaragua. There is limited information about the environmental conditions of the area prior to geothermal development, however through an intensive literature review and satellite images processing from different years after the Momotombo power plant commissioning, a comprehensive analysis is carried out to understand changes in land use and the evolution of vegetation cover in time.

2. BACKGROUND OF THE MOMOTOMBO GEOTHERMAL FIELD

2.1 History of Development

The first studies about the geothermal potential in Nicaragua started in 1966 to discover and delineate potential geothermal reservoirs in western Nicaragua. Exploration in the Momotombo field began in 1970 using geological, geochemical and geophysical methods and subsequent surveys by various consultants produced a number of geotechnical reports on the geology, geophysics, and geochemistry of the field as well as describing production well drilling (U.S. Department of Energy, 1982).

Since 1966, the Momotombo area was considered for further exploration with the purpose of finding an exploitable geothermal reservoir. A summary of the development schedule based on U.S. Department of Energy (1982) and INE (1989) is featured below.

September to November 1966 - Electroconsult made a preliminary evaluation of the geothermal potential of Nicaragua.

June 1969 to February 1971 - Texas Instruments, Inc. completed a reconnaissance exploration program covering an extensive area of western Nicaragua. Its purpose was to locate and delineate a geothermal field or fields. Based on these investigations, Momotombo was chosen as a prime development target.

October 1972 to December 1973 - The United Nations Development Program (UNDP) continued studies at Momotombo and adjoining areas.

November 1974 to June 1976 - Electronconsult (ELC) planned and supervised an initial four-well exploration and development program of the Momotombo field. The result of this study was a Feasibility Report which included the first conceptual reservoir model and preliminary power development plans.

August 1975 to May 1979 - California Energy Company, Inc. continued development of the Momotombo field. Twenty-nine additional production-exploration wells were drilled. Geologic studies, subsurface temperature analyses and production well test were also performed, in addition to temperature gradient hole drilling at other locations.

January 1978 to June 1979 - International Engineering Company (IECO) performed a regional geothermal exploration program in Nicaragua, followed by detailed studies at several sites.

May 1979 to June 1979 - IECO and ENALUF (later INE) initiated a long-term flow testing for eight wells. Continuous monitoring and sampling was interrupted from mid-June until late September, when work recommenced.

August 1979 to 1980 - Electroconsult was involved with Instituto Nicaraguense de Energia (INE) in continuing the well testing program, reservoir engineering studies, and subsequent plant design. Organizacion Latinoamerica de Energia (OLADE) and their consultants also contributed technical support to INE at Momotombo.

March 1981- The Italian company SICOM began civil works and electromechanical assembling for the first 35MWe generation unit. The Italian consortium GIE was the equipment supplier.

March to September 1983 – The feasibility study for a second 35MWe generation unit was completed and the first 35MWe generation unit was commissioned.

November 1986- Construction works for the second 35MWe generation unit started with the participation of the following companies and organizations: GIE, CIDA, SICOM and DAL S.p.A.

March 1989- Commissioning of the second 35MWe generation unit.

October 2002 - A 7 MWe Ormat Electricity Converter (OEC) unit was commissioned.

2.2 The Creation of the Momotombo Volcanic Complex Nature Reserve

The Momotombo Volcanic Complex was declared a Nature Reserve based on Decree No. 1320 from September 1983 which states the creation of nature reserves in the Pacific of Nicaragua. The protected area was created after the construction works for the first 35 MW generation unit in the Momotombo Power Plant concluded in September 1983.

The protected area covers 148.44 km^2 where Tropical Dry Forest is the prevailing ecosystem and the main economic activities in the surrounding villages include farming, livestock, hunting and fishing in the Xolotlán Lake. The first management plan for the area was published by the Ministry of the Environment and Natural Resources (MARENA) in 2008, defining conservation subjects the Tropical Dry Forest and the white-tailed deer (MARENA, 2008).

The geothermal use zone is clearly defined in the management plan, which does not set limits for geothermal development within the concession boundaries, but a possible field expansion outside of its current geographical area is restricted by the boundaries of the nature reserve.

The administration of the protected area is in charge of MARENA and the Municipality of La Paz Centro, having the responsibility to coordinate actions with local stakeholders. The absence of permanent park rangers in the area limits the surveillance activities to control the access of poachers and villagers that enter the area for firewood extraction purposes.

In cooperation with the local authorities, the Momotombo Power Plant established a security checkpoint in the main access road to the protected area and the geothermal field. For this, security personnel keep records of the people entering the area and any suspicious activity is reported to the competent authorities to contribute to the protection of the southern part of the nature reserve.

2.3 Land Use in the Momotombo Geothermal Area

There is limited or no data about vegetation coverage in the Momotombo geothermal area from the time when geothermal exploration started. Some exploration reports mention the existence of natural features in the area, Texas Instruments noted that hydrothermal altered areas were devoid of vegetation and some of it were mapped (U.S. Department of Energy, 1982).

BID-OLADE (1993) briefly describe the main environmental issues associated to the Momotombo Geothermal development, explaining that during the drilling of the first wells in 1974, no environmental management of the operations was in place, leading to deforestation of about 6 km^2 of secondary forest, which prevailed in the area. On the other hand, the agricultural and commercial activities near the geothermal field caused deforestation of the area before geothermal development. However, the activities of the geothermal project accelerated the process due to land use change for geothermal development (drilling of boreholes, power plant construction, roads opening and arrival of settlers).

3. REMOTE SENSING FOR GEOTHERMAL RESEARCH AND ENVIRONMENTAL APPLICATIONS

Remote sensing has been widely used for mapping soil temperature and surface manifestations for initial exploration purposes in geothermal prospects. In some countries with extensive geothermal development, geothermal features as fumaroles, hot springs, mud pools, soil temperature and vegetation coverage have been used as indicators of changes associated to geothermal utilization.

The use of remotely sensed data in natural resources mapping and as source of input data for environmental modeling has become a common practice in recent years. The evolution of satellite sensors resolution and the availability of free data from different of various platforms with a wide range of spatiotemporal, radiometric and spectral resolutions has made remote sensing as, perhaps, the best source of data for large scale applications (Melesse et al. 2007). Some of the most common applications covers land use change monitoring, climate change, hydrological modeling, watershed mapping, fractional vegetation cover, impervious surface area mapping, urban modeling and drought predictions based on soil water index derived from remotely sensed data, etc.

3. METHODS

3.1 Satellite Images Selection

For obtaining and generating data from satellite images, two of the main remote sensors of free access were used, the Landsat historical data series which has data from around the world for approximately 30 years and for the current scenario Sentinel2 was used. The Landsat Mission was put into orbit on July 23, 1972 with the first generation of Landsat 1 satellites initially called ERTS-1 (NASA, 2019).

The Landsat program is the longest-running enterprise for acquisition of satellite imagery of Earth. On July 23, 1972 the Earth Resources Technology Satellite was launched. This was eventually renamed to Landsat. The most recent, Landsat 8, was launched on February 11, 2013. The Landsat sensor has a spatial resolution of between 15 and 60 meters, with an average spatial resolution of 30 meters, which makes it one of the highest resolution open access sensors; in addition to this the satellite family has a spectral resolution of 9 bands which allows it to be applied to a wide range of Earth observation fields (NASA, 2019)

Currently, the Landsat program represents the largest open-access image database in the world with a rotation period of 99 minutes; The Landsat mission is equipped with specific instruments for multispectral remote sensing, which makes the data collected highly accurate for historical analysis.

The second data source used for the analysis was Sentinel-2, an Earth observation mission from the EU Copernicus Programme that systematically acquires optical imagery at high spatial resolution (10 m to 60 m) over land and coastal waters. The mission is a constellation with twin satellites (Sentinel-2A and Sentinel-2B) that supports a broad range of services and applications such as agricultural monitoring, emergency management, land cover classification and water quality.

Satellite images from the Momotombo geothermal area available for the years 1989, 1998 and 2009 were obtained from the Landsat series. The image for the year 1989 was obtained from Landsat 5 data collection, and the 1998 and 2009 images from Landsat 7. The main reason for using Landsat for the early years analysis is because the Landsat Program has the most complete data collection of images of the world with the highest accuracy in spectral resolution compared to other sensors.

The image for the year 2018 was obtained from Sentinel-2A, one of the highest precision satellites in spatial resolution available for free access, even exceeding the Landsat Program spatial resolution. The satellite images used were downloaded from the Open Access Hub platform of the European Space Agency (ESA) and the U.S. Geological Survey (USGS) 'Earth Explorer' website.

3.2 Images Processing

Selected satellite images were obtained and prepared to extract what is known as the vegetation mosaic through the Normalized Difference of Vegetation Index (NDVI). The Vegetation Index estimates the quantity, quality and development of the vegetation through the combination of spectral bands captured by the sensor, in other words, it expresses the spectral response or electromagnetic refraction of a surface and the contrast of the vegetation with other landscape elements such as soil, water infrastructure etc. The equation used to estimate the Vegetation Index is as follows:

$$NDVI = \frac{TM_4 - TM_3}{TM_4 + TM_3} \tag{1}$$

where *TM,* is the thermal infrared band.

The NDVI is based on the particular radiometric behavior of vegetation; a vegetative cover in good health has a characteristic spectral signature due to the contrast between the red bands (between 0.6 and 0.7 µm) which is largely absorbed by the leaves and the near infrared (between 0.7 and 1.1 µm) in which most of the energy is reflected. The range of values of the spectral reflectance is between 0 and 1 since both the near-infrared reflectivity and the red reflectivity are quotients of the radiation reflected on the radiation emitted by the vegetation, therefore the NDVI values vary between -1 and 1.

The land use analysis was made through satellite image classification and individual definition of classes for each image selected. For comparison of results between years, a mapping homologation was undertaken by using a sub pixel analysis to set an appropriate threshold for comparison, which was defined based on the spectral signature of the image.

3.3 Preparation of land use and land cover classification legend

Once all the components of the satellite images have been analyzed, the legend of current land use is prepared, which reflects the grouping of the roofs in more general units in which the prevailing plant formations present in the study area are prioritized. The defined categories were the following:

Closed Broadleaved Forest: This class refers to angiosperms (wide leaves), which has the characteristic of presenting very dense areas of forests with more than 70% canopy coverage, trees with heights greater than 15 m, trunk diameter greater than 90 cm and own phenological development of each species and where the anthropogenic intervention is not observable even with satellite images.

Agricultural: These areas do not have forests, most of the vegetation coverage is composed of pastures and/or crops with scattered trees, the pastures can be managed or not, cultivated or growing naturally.

Young Secondary Forest (Tacotal): This class mainly includes the woody successional vegetation of a tropical forest. Some adult trees reach 20-25 m high, but most of the vegetation is no more than 6 m in height.

4. RESULTS AND DISCUSSION

The results of processing different satellite images from the Momotombo geothermal concession area are presented in Figures 1 to 4. In the year 1989, the composition of land use was dominated by bare ground and agricultural areas, which covered most of the concession, noting that bare ground and pastures also covered a significant area and forest, or similar vegetation only covered small patches of the geothermal field. In later years, the vegetation cover was slowly increasing, noting that tacotal and shrub vegetation covered most of the concession area and after two decades the development of a successional tropical dry forest is clear as shown in Figure 3 and 4.

The analysis of land use change during the period from 1989-2018 shows that the Momotombo geothermal area has significantly recovered the forest areas, transforming the ecosystem from productive areas (agriculture and livestock) to a type of secondary forest, which has favored the recovery of flora species and possibly the wildlife species associated with this type of habitat. In addition, tacotal and shrub vegetation have recovered almost 90% of the geothermal field, being a good indicator of the environmental management that has been taking place within the geothermal complex and of how these areas have favor natural regeneration of vegetation.

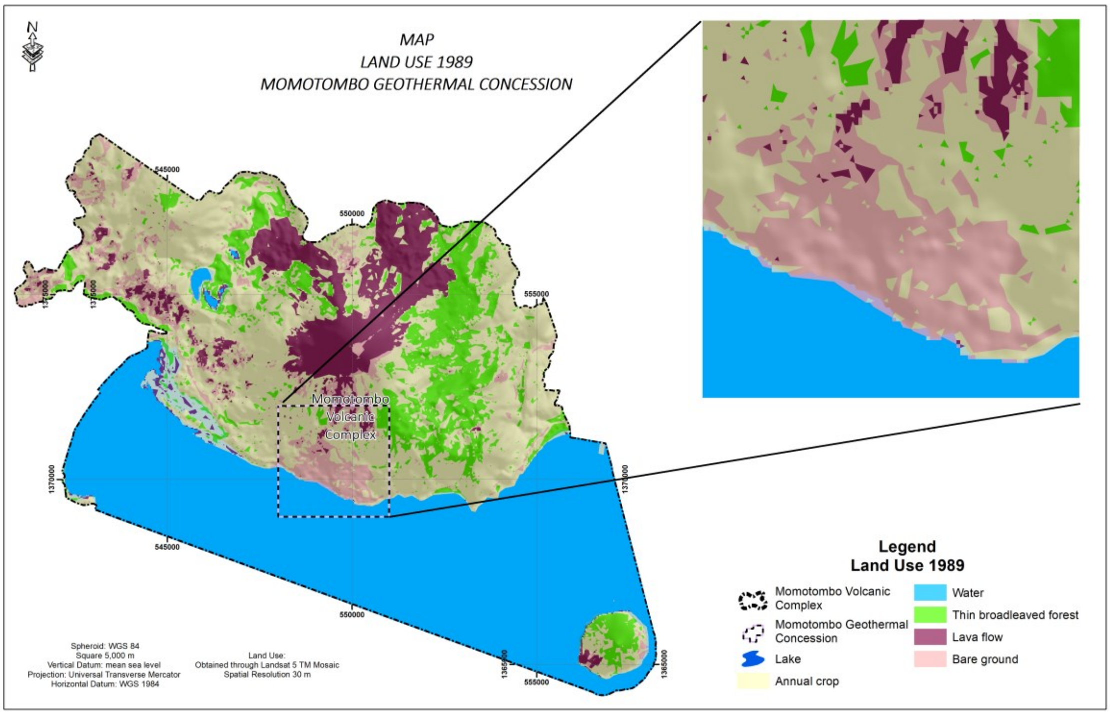

Figure 1: Land use in the Momotombo Geothermal Concession in 1989

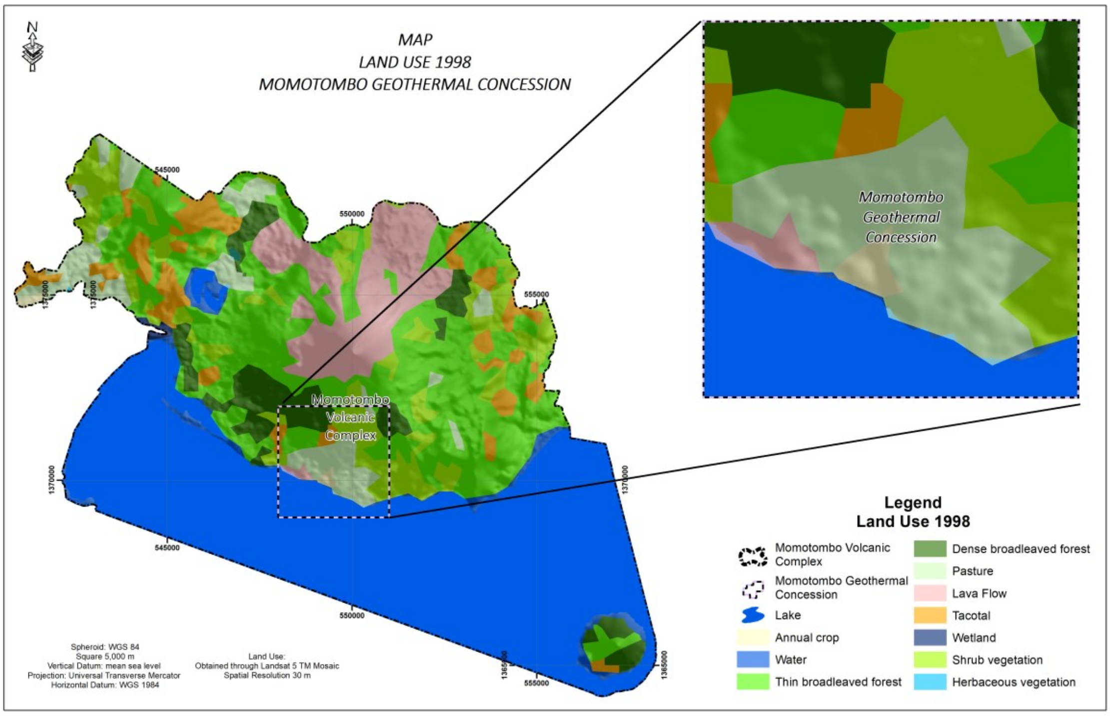

Figure 2: Land use in the Momotombo Geothermal Concession in 1998

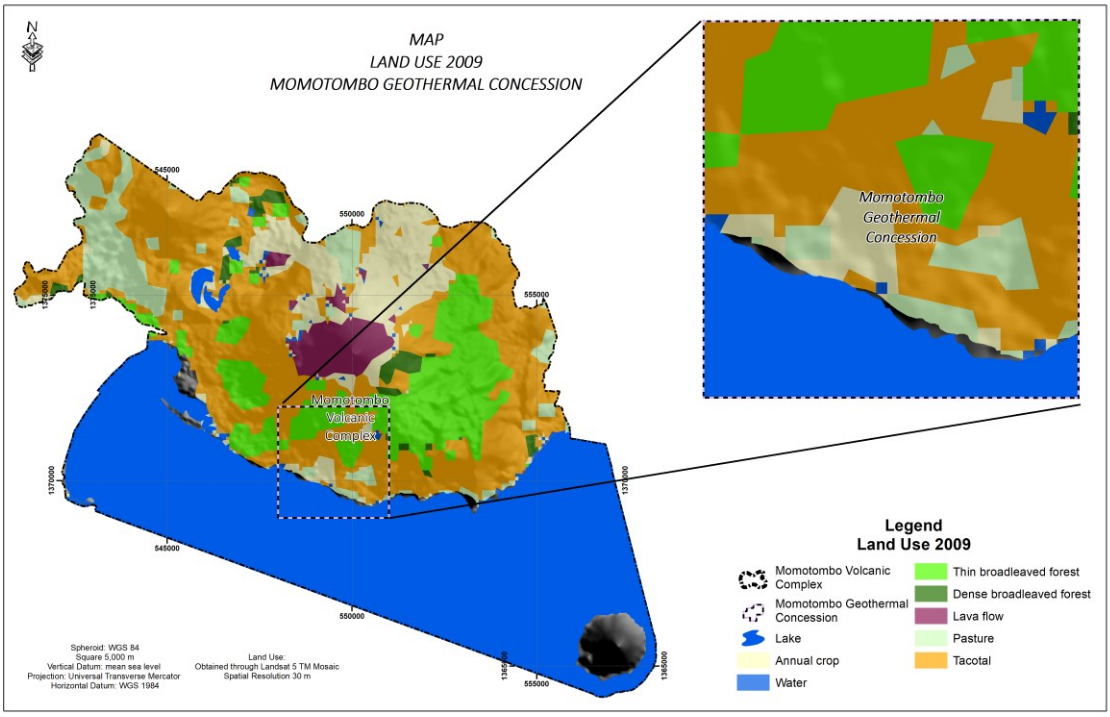

Figure 3: Land use in the Momotombo Geothermal Concession in 2009

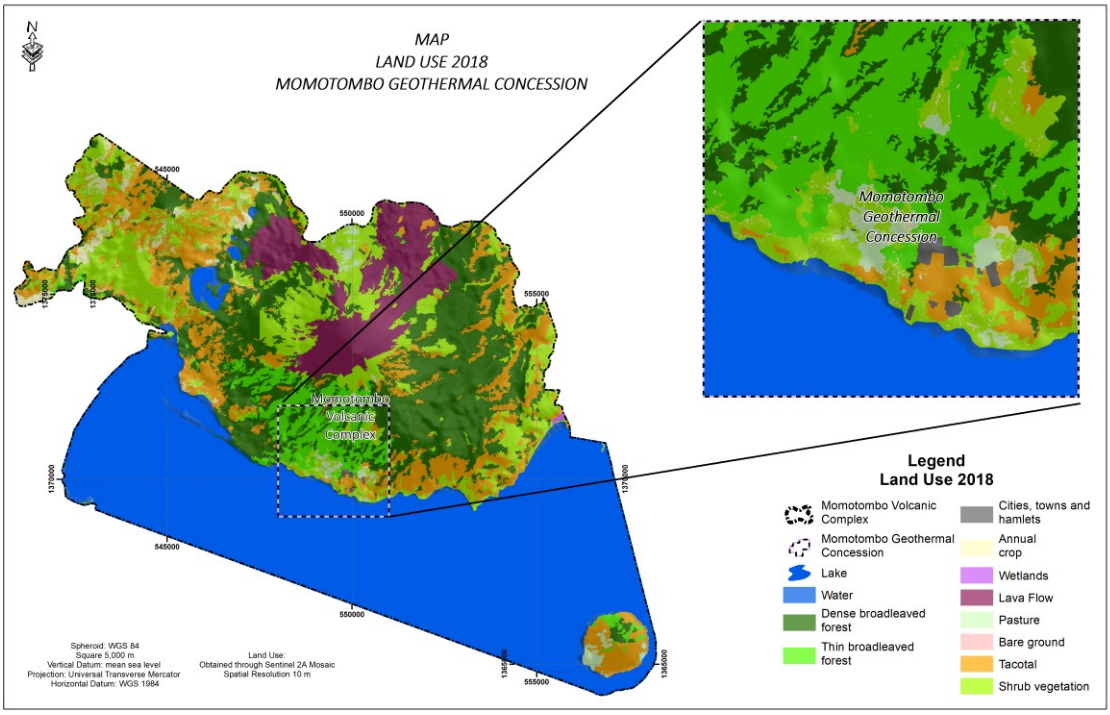

Figure 4: Land use in the Momotombo Geothermal Concession in 2018

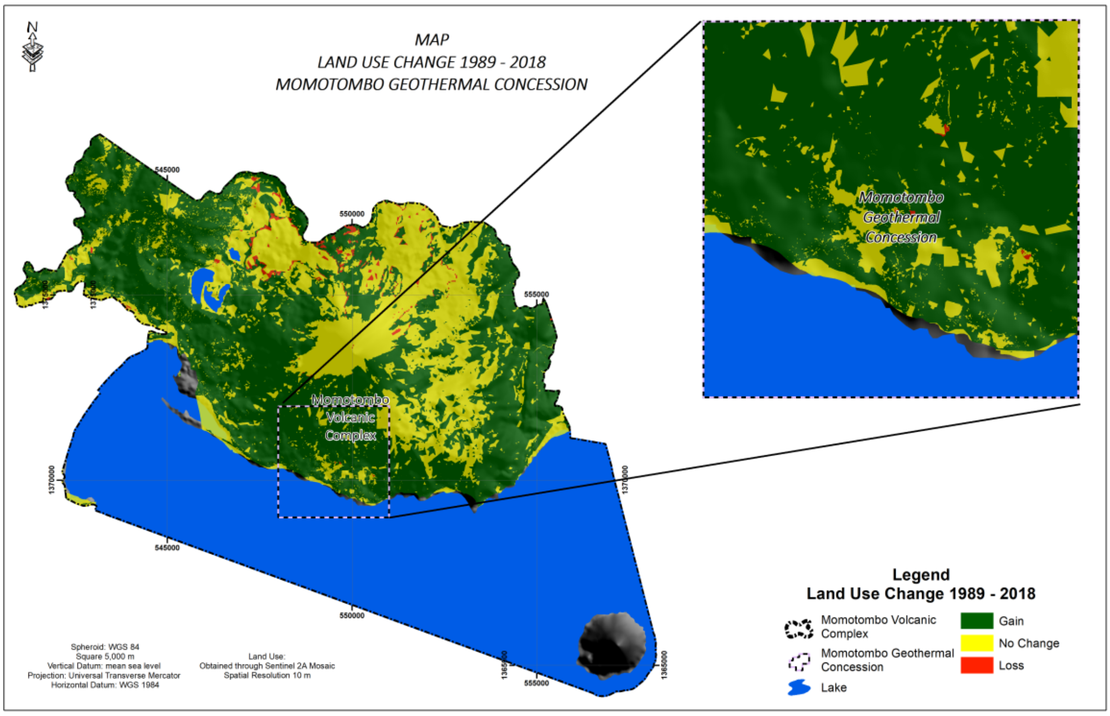

Figure 5: Vegetation cover change in the Momotombo Geothermal Concession from 1989 to 2018

The general vegetation cover gain and loss from 1989-2018 within the geothermal concession area is presented in Figure 5. Additionally, the total gain or loss for specific land use categories during three different periods is presented in Figure 6. Between 1989 and 1998, dense broadleaved forest recovered 105 ha and thin broadleaved forest gained 52 ha, while shrub vegetation class gained most of the area (189 ha). From 1998 to 2009, tacotal cover gained 319 ha and thin broadleaved forest gained 94 ha, the latter has kept the same trend during the last ten years. This vegetation development is indicative of how natural regeneration has been properly managed in the geothermal field. Furthermore, the areas dedicated to pastures and agriculture registered a significant decrease for the same period, suggesting that the soil suitability has changed, and the forest has been allowed to regenerate.

In the case of the 2009-2018 period presented in Figure 6b, there was a slight decrease in forest areas, mainly dense broadleaved forest, however there has been a significant increase in areas covered by thin broadleaved forest (110 ha). When compared to the previous period analyzed, it is noted that the gain in the forest area could be associated to better protection measures in the area during the last ten years.

Figure 6. Land use change for three different periods between 1989 and 2018

The total land cover change for the period 1989-2018 is summarized in Figure 7. Tacotal area shows the greater cover gain (50%); while dense broadleaved forest and shrub vegetation equally gained 17% of the concession area. This vegetation behavior indicates that the geothermal concession area is in the process of transition to a more mature secondary forest, with development of typical tree species of tropical dry forest. Additionally, in Figure 8 the dynamic of land use change for the same period shows a similar trend, where tacotal, dense broadleaved forest and thin broadleaved forest have significantly increased in the area over the last 10 years.

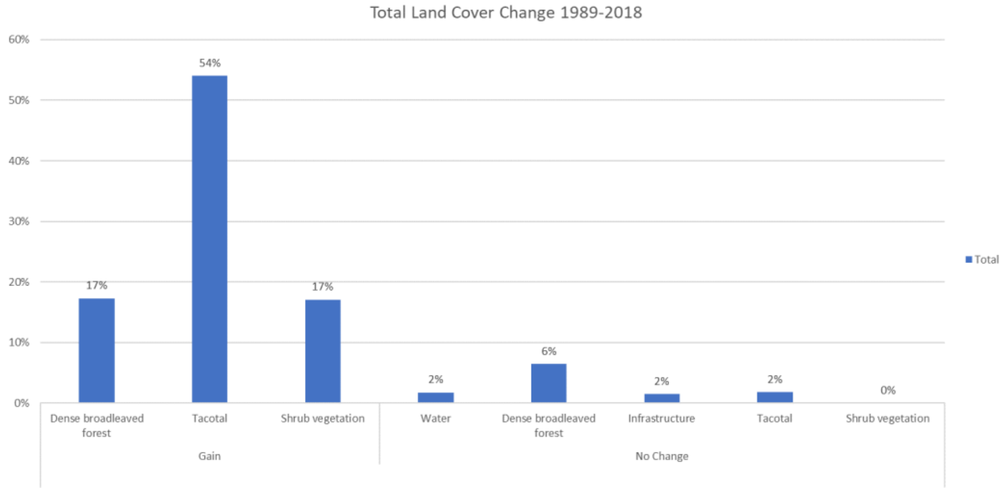

Figure 7. Total Land Use Change from 1989 to 2018

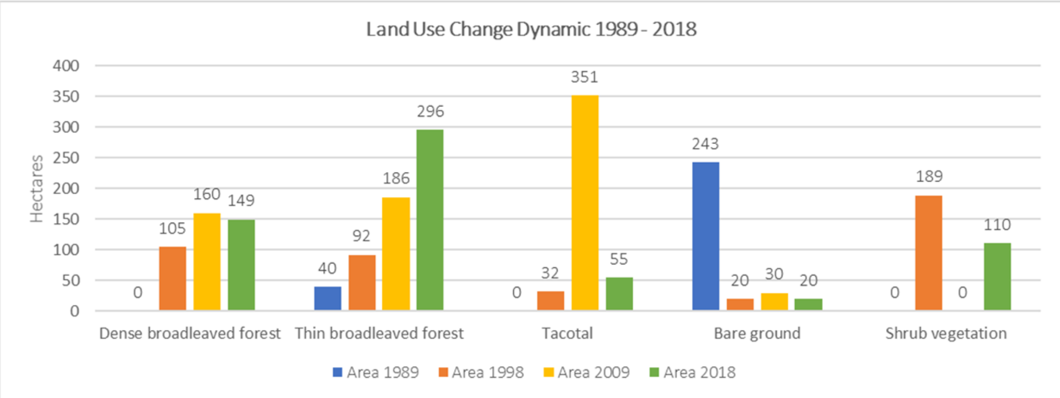

Figure 8. Land Use Change Dynamic from 1989 to 2018

4. CONCLUSSIONS

The development of the Momotombo geothermal field accelerated the land use change during the first years of operation of the power plant and steam field, which was mainly related to the opening of access roads for well pads and civil works for the steam gathering system. After the power plant was commissioned, the area started to slowly recover some of the vegetation.

The operation of the Momotombo power plant over the past 20 years has positively contributed to land reclamation and forest regeneration within the geothermal concession area. The result of the implementation of different environmental measures as reforestation, natural regeneration management and the establishment of security checkpoints to control access to the protected area during the last 10 years is inferred from the multitemporal satellite images analysis.

Further research needs to be done to determine the contribution of environmental management implemented in the geothermal field to biodiversity conservation in the Momotombo Volcanic Complex Nature Reserve.

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