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Original Article

Satellite-Based Damage Assessment Following a Wildfire Event in Cordillera de Sama Bolivia

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Abstract *- Each year, one of the countries most affected by forest fires is Bolivia, affecting 4% of its total territory. In 2017, a combination of environmental and human factors triggered a forest fire in the Cordillera de Sama Biological Reserve. This reserve houses species of flora, fauna and essential hydrographic basins for the region. Given this event, the present study uses Landsat 8 satellite imagery to calculate the Normalized Burn Ratio (NBR), the Normalized Burn Ratio - Thermal (NBRT1) and the Differenced Normalized Burn Ratio (ΔNBR) in order to develop a satellite-based evaluation of the recovery following this wildfire event in Cordillera de Sama Bolivia. These indices were extracted from one pre-fire and five post-fire satellite imagery from 2017 to 2021, and it was found, analyzing the NBR, that the total burned area in 2017 was 122.1471 Km² and in 2021 was 17.2494 Km², registering a recovery of 85.88%. Finally, analyzing the ΔNBR, a reduction of 96.29% was observed in the area classified in the category of high-severity burn throughout the five years of study.*

Keywords *- Recovery evolution, Burn severity, NBR, NBRT1, ΔNBR.*

1. Introduction

According to data from the Ibero-American Network of Climate Change Offices (RIOCC) in Ibero-America, more than 40 million hectares have been burned annually; this represents between 7% and 14% of the area burned worldwide [1]. The United Nations Office for Disaster Risk Reduction (UNDRR) indicates that forest fires in 2020 caused an economic loss of US$ 11.2 billion globally [2].

The Country Environmental Profile (PAP) prepared by the European Commission [3] indicates that Bolivia is a country with a high vulnerability to natural disasters and a high Global Climate Risk Index since the Andean country is ranked 28th among the most vulnerable countries.

The RIOCC report for the year 2020 [1] indicates that the most affected countries in terms of area burned by forest fires each year are Brazil and Bolivia, with an affectation of 4% of their respective territories. A cumulative total of 32 million hectares were burned throughout the Bolivian territory from 2000 to 2013 [4].

According to [3], one of the Bolivian regions with the highest propensity for natural disaster risk situations is the mesothermal dry valleys located in the departments of Potosí, Chuquisaca and Tarija, which are already subject to extreme droughts. It is precisely in the department of Tarija that, in 2017, a forest fire occurred in the Cordillera de Sama National Reserve.

In addition, some policies adopted by the Bolivian State negatively impacted the environment and became favorable factors for large-scale forest fires. The Bolivian State, prioritizing economic growth based on agricultural activities, proposed the "Patriotic Agenda 2025", which contemplates the expansion of the agricultural frontier from the three million hectares it had in 2013 to 13 million hectares [3]. Years later, on July 9, 2019, the Bolivian authorities approved the modification of Supreme Decree 26075 [5] on Permanent Forest Production Lands, which authorizes the clearing and controlled burning of private and community land, mainly in the departments of Beni and Santa Cruz.

Earth observation satellites have many applications. For example, monitoring of biodiversity and the environment, mining and geology, exploration of ocean resources, epidemiology, agriculture, monitoring of water resources, natural disaster management and urban planning, among others [6].

The disaster management cycle has the following stages: preparedness, mitigation, disaster event occurrence, response and recovery. The first two are focused on preparation for an event that may occur, the third is the occurrence of the disaster itself, and the last two stages are responding to an event that has occurred [7]. One type of disaster is forest fires, which comprise three stages. First is the initiation, when the fire starts as a result of natural causes or by anthropogenic causes. The second stage is the spread of the fire through nearby vegetation. Finally, the third stage is extinguishing the fire due to natural causes or firefighting [8].

Satellite technology is crucial as it provides essential information for each stage of the disaster management cycle and the different stages of a forest fire. Remote sensing is helpful for fire danger assessment, detection of active fires, measurement of fire effects and monitoring of post-fire recovery [9, 10]

For example, remote sensing satellites can provide information on hot spots, that are, places on the earth's surface with high temperatures [11, 12]. This information helps emit alerts of possible forest fires. Besides, Earth observation satellites are also helpful in detecting active forest fires and observing their spread [13, 14] to alert the population that may be at risk. Finally, once the forest fire has been extinguished, remote sensing can provide information to identify the number of hectares affected by the fire and the levels of damage [15, 16] and develop post-fire recovery monitoring [17, 18].

Regarding the use of remote sensing techniques to measure fire effects, develop a damage assessment and monitor post-fire recovery can be seen in various studies. Using different remote sensing satellites such as Landsat 8, Moderate-Resolution Imaging Spectroradiometer (MODIS) and Sentinel- 2A and 2B. In these works, various burn indices such as NBR, NBRT1 and ΔNBR were calculated in pre-fire and post-fire satellite images to perform a wildfire damage assessment, identifying the burned areas and mapping the burned area results [18, 19, 20, 21, 22].

Given this situation, the present study aims to develop a damage assessment following a wildfire event in Cordillera de Sama, Bolivia. For this purpose, Landsat 8 satellite will be used to analyze pre-fire and post-fire satellite imagery from 2017 to 2021, to calculate burn indices such as the Normalized Burn Ratio (NBR) and the Normalized Burn Ratio - Thermal (NBRT1). In order to identify areas that have been more affected due to the fire and the evolution of burn severity in the area over time, the Differenced Normalized Burn Ratio (ΔNBR) will be analyzed.

The present study aims to provide information on this disaster and develop a damage assessment over time to help the corresponding authorities make better decisions based on satellite information.

2. Wildfire Event

In order to describe the wildfire event that occurred in Cordillera de Sama, it is necessary to remember the three stages of a forest fire: initiation, spread and extinguishing [8].

The initiation stage of the forest fire began on August 8, 2017, in the Cordillera de Sama Biological Reserve (RBCS), located in southern Bolivia. This biological reserve is one of the 22 protected areas in the country [24].

Investigating, it was identified that the forest fire originated in the Erquis Ceibal community [25]. According to the authorities, two possible causes were determined, a resident who left a stove lit in her home [26] and garbage burning in a nearby community [24]. The truth is that the cause of this forest fire was anthropogenic since it was produced by human action.

However, the causes of a forest fire can be multiple. In this case, it is crucial to analyze the natural conditions that could have contributed to the occurrence of this event.

According to [27], there is an interaction between extreme drought conditions and the rapid expansion of the agricultural frontier, which further increases the risk of forest fires in the region.

Deforestation is a significant problem in the country because, according to the 2020 report of the Food and Agriculture Organization (FAO), Bolivia is among the ten countries worldwide with the largest deforested area, with an average deforestation rate of 225.2 thousand ha/year for the period from 2010 to 2020 [28]. Unfortunately, this deforestation in the country's territory has increased soil moisture loss.

Furthermore, the deterioration of environmental quality and the process of expanding the agricultural frontier has increased rapidly in the last thirty years [3]. Mainly because the authorities little regulate the change in land use, there is a conversion of land from forest to agricultural land. According to the Forest and Land Inspection and Social Control Authority (ABT), more than 50% of the change in land use in the department of Santa Cruz for the years 2014-2017 is illegal [29]. This accelerated and poorly controlled agricultural frontier expansion has contributed to intense droughts in various regions of the country.

Droughts in the country are also a factor to consider for forest fires. According to the National Program of the United Nations Office for the Coordination of Humanitarian Affairs, until September 2016, eight of the nine departments of Bolivia were affected by droughts. Therefore, 51% of the country's municipalities declared an emergency and more than 172 000 affected families were reported [30].

The meteorological drought affects the Chaco region, the departments of Santa Cruz, Chuquisaca and Tarija. In addition, 67% of the Bolivian territory is affected by aridity phenomena [31]. In addition, according to [32], it was estimated that by 2030 27% of the Bolivian territory could be affected by droughts. The propagation stage of this forest fire was reported first in the east-west direction with a length of 17 kilometres and, secondly, in the north-south direction with a length of 6 kilometres [26]. The forest fire lasted five days and destroyed approximately 10 600 hectares of the Cordillera de Sama Biological Reserve. This affected area represents 10% of the total surface of this biological reserve [24].

It is essential to mention that 70% of the area damaged by this forest fire corresponds to the protected area, and 30% corresponds to the area inhabited by rural communities [26]. Due to this, a loss of livestock was recorded since at least 3 000 families in rural communities dedicated to agriculture and livestock lost their animals and crops [24]. Likewise, the forest fire harmed the capacity of the Cordillera de Sama to collect water since this mountain range supplies water to the entire central valley of Tarija [33]. Fire damaged the most extensive water reserve in La Victoria and the natural swimming spot in San Pedro de Sola, one of the most significant tourist attractions in the region. In addition, this forest fire left a balance of three people dead and ten injured [26, 34].

Finally, on August 13, 2017, the fire extinction stage was reported. Thanks to the organization and deployment of the authorities, civilian volunteers, firefighters, military personnel, police personnel, and aerial equipment, the forest fire was utterly extinguished [24]. This forest fire was catalogued as the worst that Bolivia has suffered in the last 15 years [34].

3. Satellite-based Damage Assessment

This section describes the selected study area, identifies the data sets used for the analysis, and describes the methodology developed for image processing and damage assessment of the area affected by the forest fire in Cordillera de Sama.

3.1. Study Area Description

As mentioned above, the area affected by the forest fire was the Cordillera de Sama Biological Reserve, located in the department of Tarija in Bolivia.

3.1.1. Sama Forest

Cordillera de Sama Biological Reserve extends into the provinces of Eustaquio Méndez, Cercado and José María Avilés. Located in the western region of the department of Tarija, this reserve occupies 108 500 hectares in these provinces [35]. This biological reserve has an altitude between 1 800 and 4 700 meters above sea level [36].

Due to this altitudinal variation, the area's climate can vary from semi-arid to temperate. Presents three main climatic types: the highest zone has a cold semi-humid climate with an average annual temperature of 9°C; the northwest zone has a semi-humid cold climate with an average annual temperature of 14°C, and in the Andean forest zone, there is a humid cold climate [35].

Cordillera de Sama Biological Reserve was created on January 30, 1991, through Supreme Decree No. 22721 [58], to protect the region's diversity of flora and fauna and to conserve the hydrographic basins that cross the area. [24], since they have a great capacity to capture and regulate water flows. This protected reserve comprises several high Andean ecological systems, and three central ecoregions are identified [58]: northern puna, inter-Andean dry forests and Tucuman-Bolivian forest.

Various flora and fauna have been identified within the Cordillera de Sama Biological Reserve [38]. Around 109 fauna species and 254 flora species have been recorded [58]. Some of these fauna species are endemic to the region, such as the Andean deer, Andean fox, vizcacha, condor, the country's emblem, and Andean flamingos [36, 38]. Regarding vegetation, the most common forest species are the alder, yareta, Kiwiña and Kiswara. [35].

Cordillera de Sama has hydrological basins of great importance; rivers such as the Guadalquivir, Tolomosa, Tajzara, La Victoria, San Juan del Oro and Camacho [36]. In addition, it has wetlands and high Andean lakes. All these basins must be protected, as they supply water to the city of Tarija and the central valley [39].

According to the report of the European Union [3], the profiles of natural and climatic risks for the Cordillera de Sama Reserve are, firstly, illegal settlements and overgrazing for livestock [38]. Secondly, constant burning, called chaqueos, produces large fires and directly impacts the habitat. Lastly, harmful activities of poaching species, plundering archaeological sites and extracting wood and guano have been identified [36].

3.1.2. Selected Study Area

According to [35], the area affected by the fire in the Cordillera de Sama Biological Reserve is located in the following geographic coordinates: (21°27'54" - 21°37'32") S of Latitude and (64°01'27 " - 64°52'21") W of Longitude. In addition, a map of the study area selected to analyse recovery following a wildfire event in Cordillera de Sama, Bolivia, can be seen in Fig. 1.

As can be seen in Fig. 1, the study area selected for this analysis focuses mainly on three provinces of the department of Tarija, which are: Eustaquio Méndez, Cercado and José María Avilés, colored in yellow, since in its interior, the Cordillera de Sama Biological Reserve is extended.

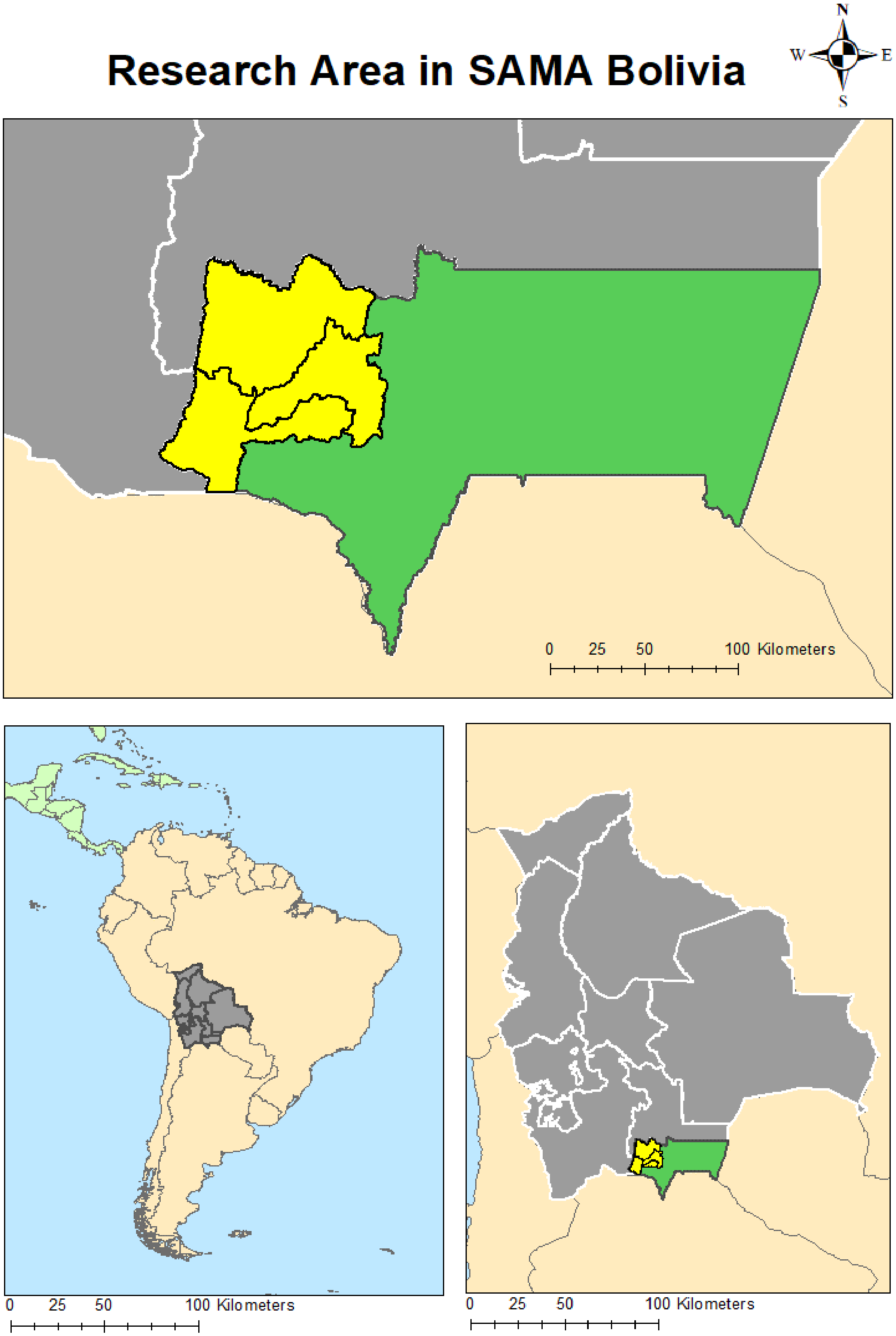

Fig. 1 Research area in Sama Bolivia

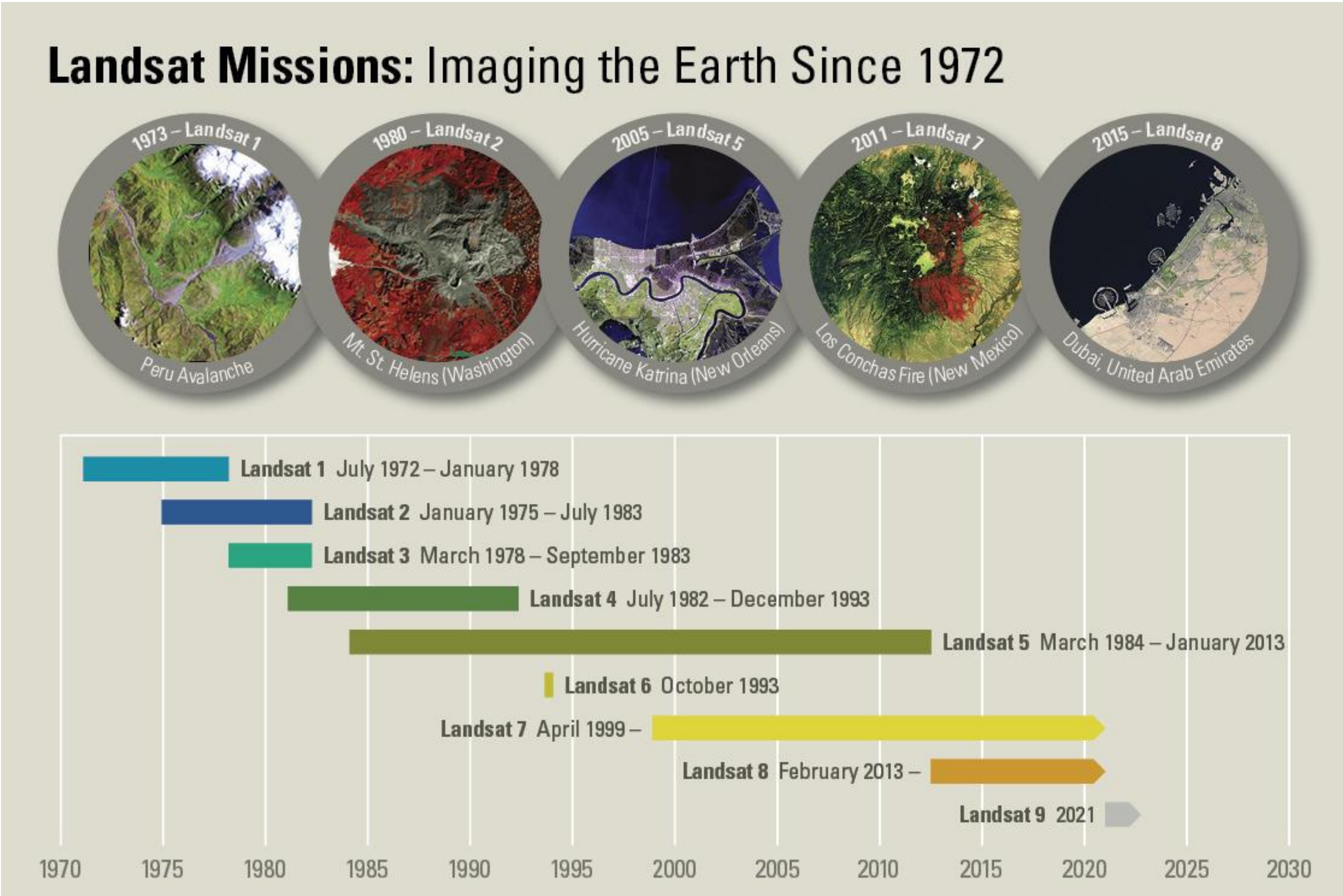

Fig. 2 Landsat missions

3.2. Data Sets

Satellite images from the Landsat 8 mission will be analyzed to develop a damage assessment in the affected area of Cordillera de Sama. This satellite is the penultimate launch as part of the Landsat project. As seen in Fig. 2, this program launched nine observation satellites [40]. The Landsat 8 satellite was launched on February 11, 2013, and is operated by the United States Geological Survey (USGS) and NASA [41].

Landsat 8 satellite carries the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) instruments. These two sensors collect image data for 11 spectral bands, as can be observed in Table 1:

Table 1. Landsat 8 spectral bands specifications

Band	Name	Wavelength (µm)	Resolution (m)
1	Ultra Blue (coastal/aerosol)	0,435 - 0,451	30
2	Blue	0,452 - 0,512	30
3	Green	0,533 - 0,590	30
4	Red	0,636 - 0673	30
5	Near Infrared (NIR)	0,851 - 0,879	30
6	Shortwave Infrared 1 (SWIR 1)	1,566 - 1,651	30
7	Shortwave Infrared 2 (SWIR 2)	2,107 - 2,294	30
8	Panchromatic	0,503 - 0,676	15
9	Cirrus	1,363 - 1,384	30
10	Thermal Infrared (TIR 1)	10,60 - 11,19	100
11	Thermal Infrared (TIR 2)	11,50 - 12,51	100

Table 2. Selected data sets

Date	Dataset	Path	Row	% Cloud coverage	Department
14/07/2017	LC08_L1TP_231075_20170714_20170726_01_T1	231	75	20	Tarija
15/08/2017	LC08_L1TP_231075_20170815_20170825_01_T1	231	75	0.57	Tarija
18/08/2018	LC08_L1TP_231075_20180818_20180829_01_T1	231	75	0	Tarija
5/08/2019	LC08_L1TP_231075_20190805_20190820_01_T1	231	75	0.05	Tarija
23/08/2020	LC08_L1TP_231075_20200823_20200905_01_T1	231	75	0	Tarija
26/08/2021	LC08_L1TP_231075_20210826_20210826_01_RT	231	75	2.3	Tarija

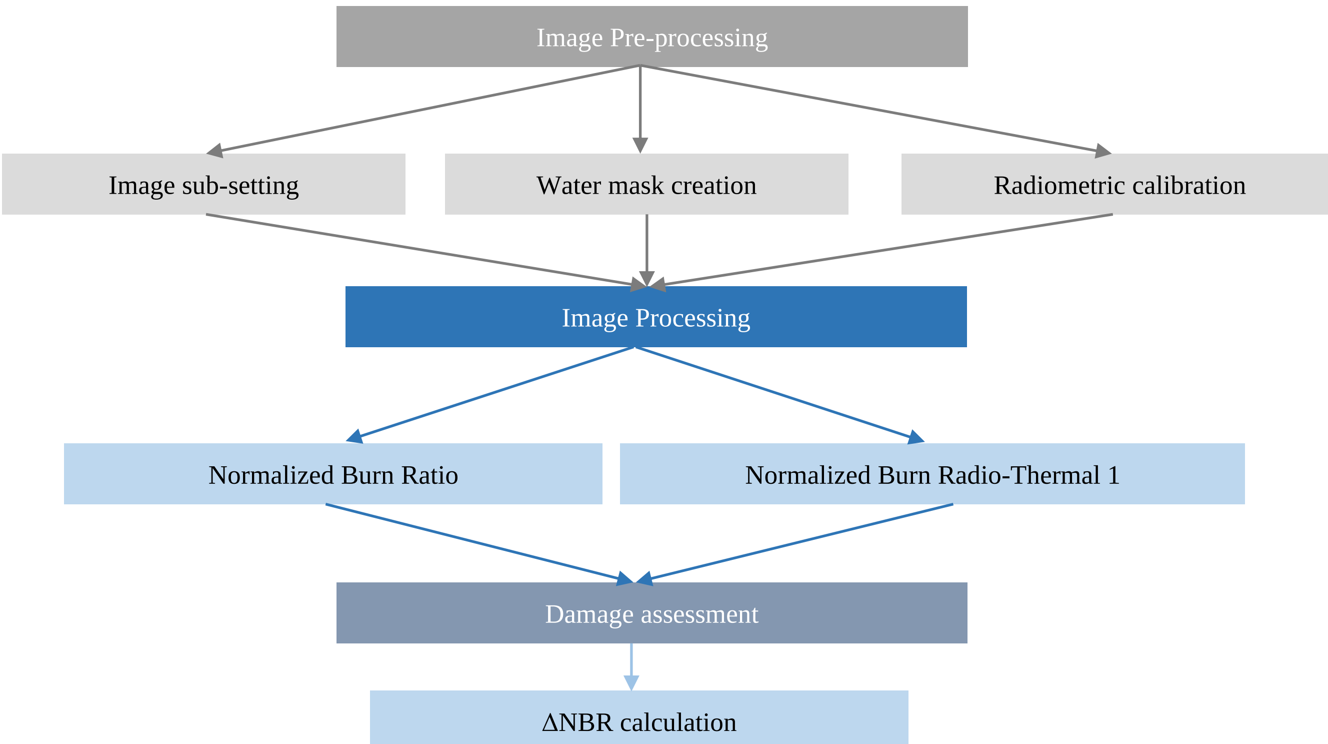

Fig. 3 Block diagram for the treatment of the images

OLI instrument measures three portions of the spectrum, the visible, near-infrared and shortwave infrared. TIRS instrument measures land surface temperature in two thermal bands [42]. As shown in Table 1, Landsat 8 images have 30-meter multi-spectral and 15-meter panchromatic spatial resolutions. Besides, this satellite has a temporal resolution of 16 days and a radiometric resolution of 12 bits [43, 44].

Landsat 8 primarily aims to provide uninterrupted data to researchers, policymakers, and others. It is for this reason that USGS has a main website to access the Landsat 8 data sets (https://earthexplorer.usgs.gov/).

Details of the data sets used for analysis in this study are presented in Table 2:

As shown in Table 2, six satellite images were processed, and one pre-fire data set (was acquired 25 days before the forest fire in the area). Five post-fire data sets, the first one acquired two days after the end of the fire and the rest one year apart until 2021. These data sets from Landsat 8 were used to perform the analysis. All the selected data sets have a cloud coverage of less than or equal to 20%.

3.3.Treatment of Satellite Images

The general block diagram for the treatment of the images developed in the present study can be seen in Fig. 3:

The methodology to develop the treatment of the six analyzed data sets is divided into three phases. Firstly, in the pre-processing stage, it will be necessary to cut the original satellite image to focus on the area of interest and optimize processing time. Subsequently, a water mask will be developed, establishing a threshold to mask water bodies and exclude these pixels from the analysis. The near-infrared band (NIR) is used for this step because the water pixels register a low reflectance in this spectral band. It is important to highlight that this step was mainly applied to data sets with water bodies in the area of interest since the burn indices calculated are sensitive to water. These pixels can be erroneously classified as high-severity burns. Finally, a radiometric calibration stage is developed to calibrate the cropped satellite image's multi-spectral and thermal bands. The multi-spectral bands were calibrated to top-of-atmosphere (TOA) reflectance, and the thermal bands were calibrated using the brightness temperature.

In order to calibrate the data sets, it is necessary to remember that according to [42], Landsat 8 products are scaled to 55 000 grey levels, and these products can be rescaled to the Top of Atmosphere (TOA) reflectance or radiance using the metadata file (MTL file) to extract their radiometric rescaling coefficients. The MTL file indicates the data set's values of offset, gain, sun elevation, solar irradiance, and acquisition time. The equation to calculate the TOA reflectance [45] is given as follows:

$$\rho_\lambda = \frac{\pi L_\lambda d^2}{ESUN_\lambda sin\Theta} \quad (1)$$

Where:
ρ_λ = Unitless TOA reflectance
L_λ= TOA spectral radiance $(Watts/(m^2 * srad * \mu m))$
d = earth-sun distance, in astronomical units
$ESUN_\lambda$ = solar irradiance $(Watts/(m^2 * \mu m))$
Θ = sun elevation in degrees

In order to calculate the radiance [46], the equation is given as follows:

$$L_\lambda = Gain * Pixel\ value + Offset \quad (2)$$

Where:
L_λ =TOA spectral radiance$(Watts/(m^2 * srad * \mu m))$
Gain $(Watts/(m^2 * srad * \mu m))$
Offset $(Watts/(m^2 * srad * \mu m))$

As mentioned before, it is necessary to calibrate the thermal bands of the satellite image using the brightness temperature in Kelvin [47, 48]; the equation is given as follows:

$$T = \frac{K2}{\ln\left(\frac{K1}{L_\lambda} + 1\right)} \quad (3)$$

Where:
T = Top of atmosphere brightness temperature (K)
L_λ = TOA spectral radiance $(Watts/(m^2 * srad * \mu m))$
$K1$ and $K2$ = Band-specific thermal conversion constants from the metadata (K)

Afterwards, the image processing stage is developed. In this stage, two burn indices were calculated, the Normalized Burn Ratio (NBR) and the Normalized Burn Ratio - Thermal (NBRT1). These indices were calculated with the following equations:

For calculating both indices, different satellite image bands were used in the spectral ranges mentioned in Table 3. Additionally, the spatial resolution of the thermal bands must be resampled to a resolution of 30 m since these bands have a spatial resolution of 100 m. For the resampling step, the cubic convolution method was used.

The Normalized Burn Ratio (NBR) [49, 51, 23] identifies burned areas in large fire zones. In order to compute this index, NIR and SWIR bands are used. As a result, the burned areas will show low reflectance in the NIR band and high reflectance in the SWIR band.

The Normalized Burn Ratio - Thermal (NBRT1) [52, 53], as shown in Table 3, has an equation similar to the NBR index, except that it uses the thermal band since this band will provide greater accuracy in the separability of the burned and unburned area.

Lastly, the third phase for the treatment of the images is the damage assessment stage in the affected area. The Differenced Normalized Burn Ratio (ΔNBR) was calculated to develop this analysis. This parameter indicates burn severity since it measures the absolute change in the NBR. To calculate this differential, subtract the post-fire NBR from the pre-fire NBR using the following equation [54]:

$$\Delta NBR = NBR_{Prefire} - NBR_{Postfire} \quad (6)$$

Table 3. Burn indices

Index	Equation	Used bands	Band spectral range (µm)
Normalized Burn Ratio (NBR)	$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}$ (4)	SWIR	2.08 - 2.35
		NIR	0.76 - 0.9
Normalized Burn Ratio - Thermal (NBRT1)	$NBRT1 = \frac{(NIR - SWIR\left(\frac{Thermal}{1000}\right)}{(NIR + SWIR\left(\frac{Thermal}{1000}\right))}$ (5)	SWIR	2.08 - 2.35
		NIR	0.76 - 0.9
		Thermal	10.4 - 12.5

Table 4. Categories of burn severity

ΔNBR values	Burn severity
< -0.25	High post-fire regrowth
-0.25 to -0.1	Low post-fire regrowth
0.1 to 0.1	Unburned
0.1 to 0.27	Low-severity burn
0.27 to 0.44	Moderate- to low-severity burn
0.44 to 0.66	Moderate- to high-severity burn
> 0.66	High-severity burn

The calculation of the ΔNBR is performed for each of the years analyzed in this study from 2017 to 2021. The results are interpreted according to [55], as shown in Table 4.

As shown in Table 4, brighter pixels indicate higher levels of burn severity in the area of interest

4. Results and Discussion

The results obtained from processing the selected satellite images of the affected area from 2017 to 2021 are described in this section.

The statistical data, calculated from the rasters resulting from the calculation of the NBR and the NBRT1 indexes, can be seen in Table 5.

The NBR and NBRT1 indexes vary from -1 to 1, where the negative values correspond to burned areas, whereas positive values represent healthy vegetated areas or in the regeneration phase. Analyzing the NBR index by the mean value of the entire area of image subsetting can be observed that the most affected data set is the post-fire image acquired in August 2017, two days after the end of the fire, since it presents the lowest mean value -0.042873. Besides, the least affected post-fire data set was acquired in August 2020, with the highest mean value of 0.035672. Analyzing the NBRT1 index by the mean value (of the entire area of the image subsetting), it can be observed that the most affected data set is the post-fire image acquired in August 2017, with the lowest mean value of 0.413757. However, according to this index, the least affected post-fire data set is the one acquired in August 2019, with the highest mean value of 0.446713.

Table 5. Statistics of the Normalized Burn Ratio (NBR) and the Normalized Burn Ratio – Thermal 1 (NBRT1)

Normalized Burn Ratio (NBR)				Normalized Burn Ratio - Thermal 1 (NBRT1)			
Min	**Max**	**Mean**	**StdDev**	**Min**	**Max**	**Mean**	**StdDev**
Date:14/07/2017 **Dataset:**LC08_L1TP_231075_20170714_20170726_01_T1							
-0.740094	0.912468	0.057094	0.132943	-0.226672	0.946191	0.454603	0.075421
Date:15/08/2017 **Dataset:**LC08_L1TP_231075_20170815_20170825_01_T1							
-0.691077	1	-0.04287	0.166626	-0.259455	1	0.413757	0.094658
Date:18/08/2018 **Dataset:**LC08_L1TP_231075_20180818_20180829_01_T1							
-0.446495	1	0.027261	0.118649	-0.051585	1	0.44084	0.068233
Date:5/08/2019 **Dataset:**LC08_L1TP_231075_20190805_20190820_01_T1							
-0.654866	0.867817	0.028616	0.125347	0.104801	1	0.446713	0.07346
Date:23/08/2020 **Dataset:**LC08_L1TP_231075_20200823_20200905_01_T1							
-0.773676	0.934486	0.035672	0.11275	-0.114269	1	0.442837	0.066183
Date:26/08/2021 **Dataset:**LC08_L1TP_231075_20210826_20210826_01_RT							
-0.685013	0.771574	0.011377	0.108533	0.090444	0.957639	0.435126	0.064379

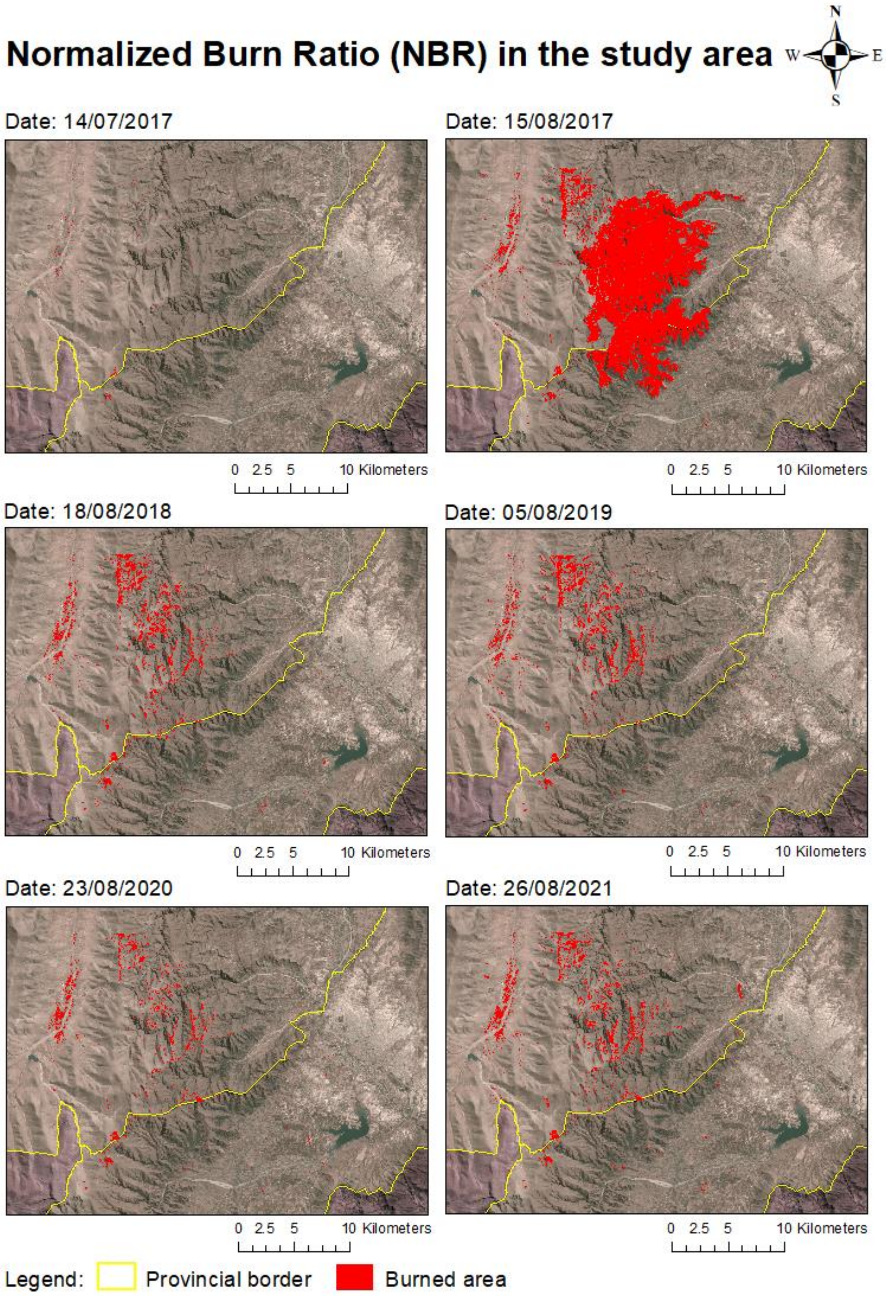

Fig. 4 Normalized Burn Ratio (NBR) in the study area

In order to quantify the degree of affectation and subsequent recovery of the area affected by the forest fire in the Cordillera de Sama Biological Reserve, Fig. 4 shows the burned areas according to the NBR index calculated from 2017 to 2021.

As shown in Fig. 4, the red-colored pixels correspond to the burned area calculated by the NBR index. In addition, the provincial boundary between the two provinces affected by the fire is observed in yellow. It is observed that there were no burned areas in the data set acquired in July 2017, evidently because this data set corresponds to our pre-fire image, acquired 25 days before the forest fire in the area.

Besides, it can be seen that the most affected province is Eustaquio Méndez, and the least affected province is Cercado. Likewise, it can be seen that the area affected by the fire has been gradually recovering from 2017 to 2021. According to the data in Table 6 for the NBR index, a recovery of 85.88% is recorded, considering that the area burned in August 2017 covered 122,1471 Km². In 2021, it covered only 17,2494 Km² of the Cordillera de Sama Biological Reserve.

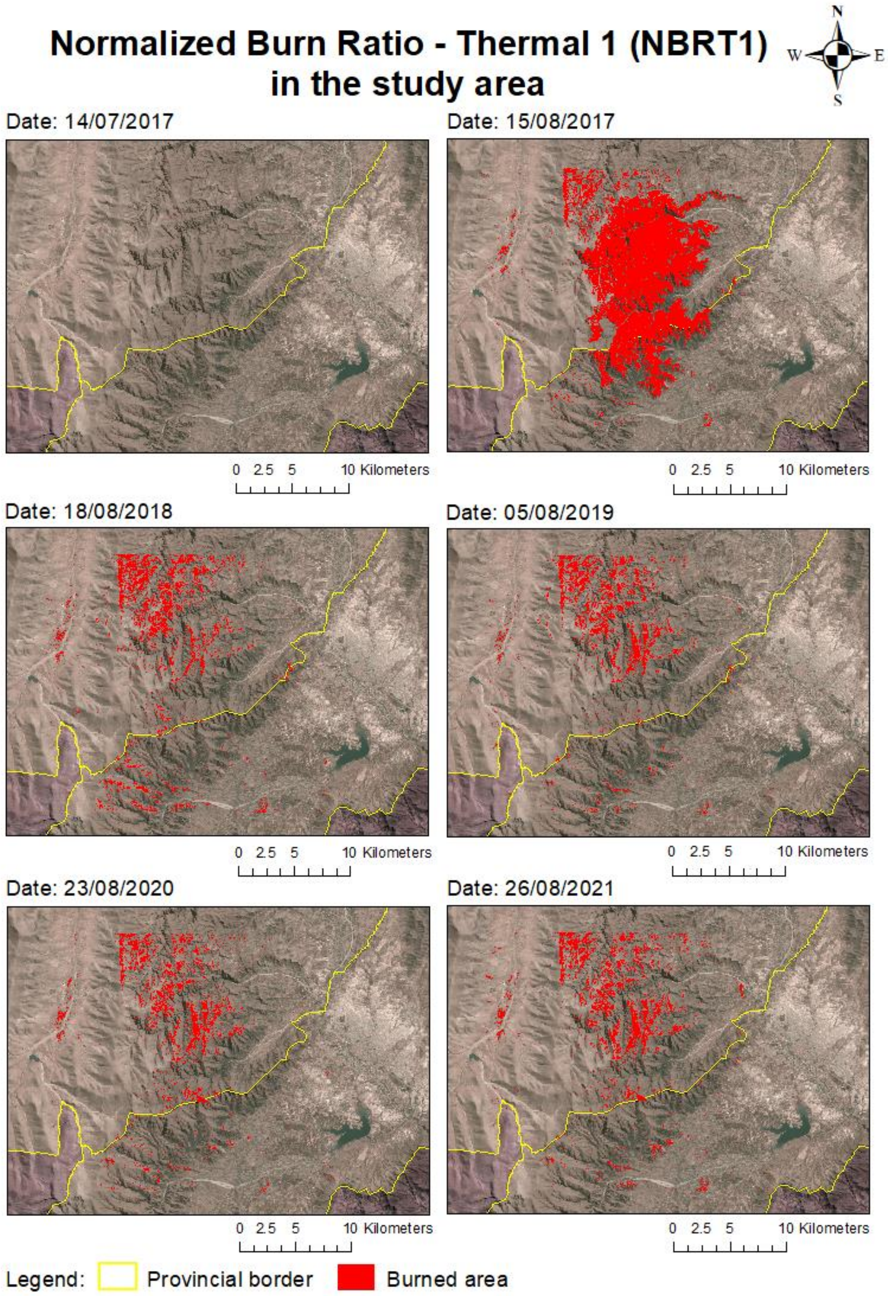

Fig. 5 Normalized Burn Ratio - Thermal 1 (NBRT1) in the study area

Likewise, in Fig. 5, the burned areas according to the NBRT1 index calculated from 2017 to 2021 can be observed.

As shown in Fig. 5, the red colored pixels correspond to burned area calculated by the NBRT1 index. Also, the provincial boundary between Eustaquio Méndez and Cercado provinces is observed in yellow.

If we compare the results with Fig. 4, it can be seen that compared to the NBR index, NBRT1 had more accuracy in classifying burned and unburned areas since it uses the thermal band to optimize the results obtained.

According to Table 6, analyzing the NBRT1 index, a recovery of 74.13% is recorded, considering that the burned area in August 2017 covered 114.2352 km² of the Cordillera de Sama Biological Reserve, and in 2021 it covered only 29.5488 km². Both indices show a favorable recovery in the area affected by the forest fire.

Table 6. Burned area calculated from the NBR and NBRT1 indexes

		Normalized Burn Ratio (NBR)		Normalized Burn Ratio - Thermal 1 (NBRT1)	
Date	**Dataset**	**Burned Area (Km2)**	**Unburned area (Km2)**	**Burned Area (Km2)**	**Unburned area (Km2)**
14/07/2017	LC08_L1TP_231075_20170714_20170726_01_T1	0.801	542.8458	0.0342	543.6126
15/08/2017	LC08_L1TP_231075_20170815_20170825_01_T1	122.1471	423.0333	114.2352	430.9443
18/08/2018	LC08_L1TP_231075_20180818_20180829_01_T1	17.0109	527.8851	29.5983	515.2977
5/08/2019	LC08_L1TP_231075_20190805_20190820_01_T1	17.6067	526.9338	26.451	518.0895
23/08/2020	LC08_L1TP_231075_20200823_20200905_01_T1	10.6434	534.2967	23.8284	521.1126
26/08/2021	LC08_L1TP_231075_20210826_20210826_01_RT	17.2494	527.8257	29.5488	515.5272

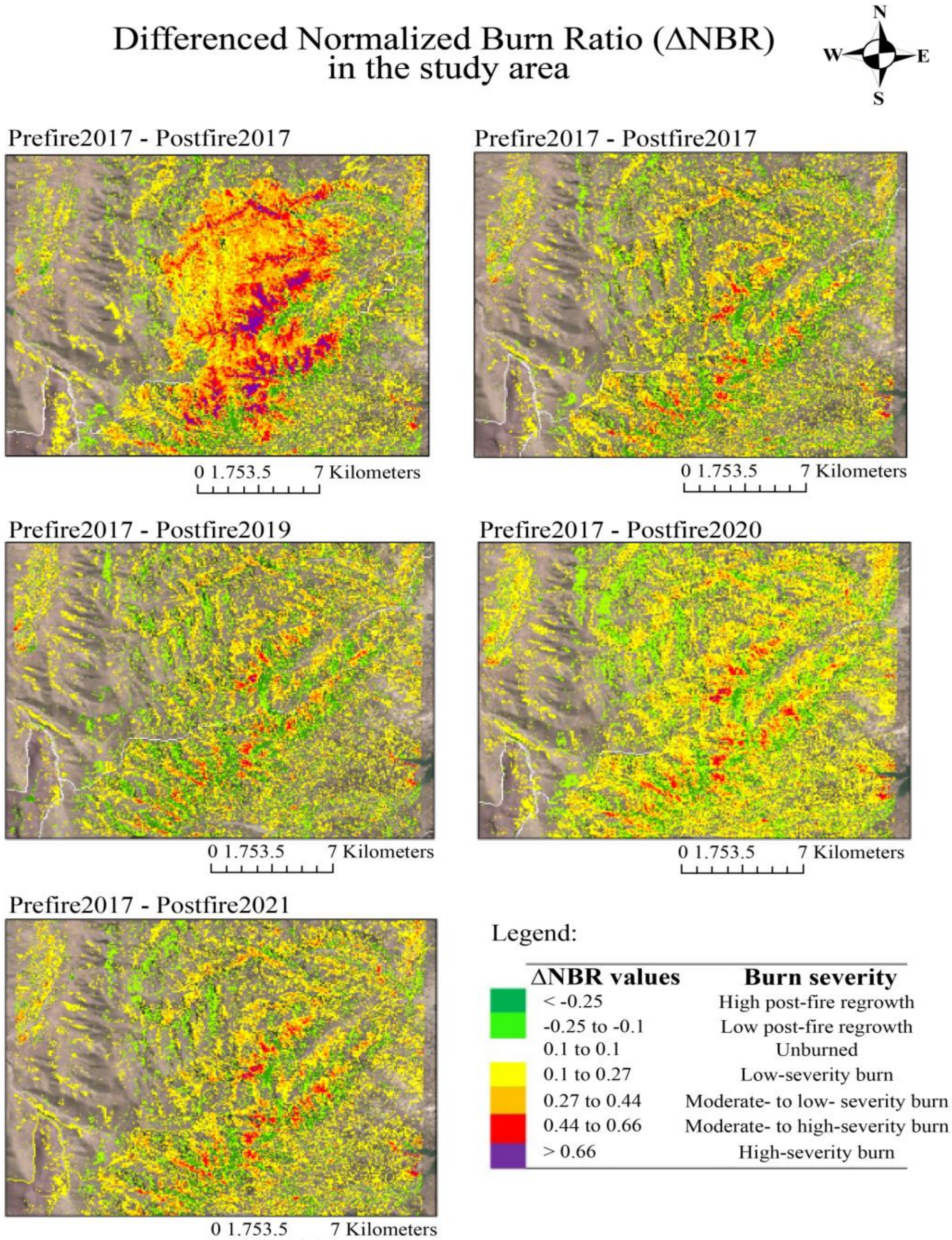

Fig. 6 Differenced Normalized Burn Ratio (ΔNBR) in the study area

Table 7. Burned area calculated from the NBR and NBRT1 indexes

Burn severity	Differenced Normalized Burn Ratio (ΔNBR)				
	Prefire$_{2017}$ – Postfire $_{2017}$ (km^2)	**Prefire$_{2017}$ – Postfire $_{2018}$ (km^2)**	**Prefire$_{2017}$ – Postfire $_{2019}$ (km^2)**	**Prefire$_{2017}$ – Postfire $_{2020}$ (km^2)**	**Prefire$_{2017}$ – Postfire $_{2021}$ (km^2)**
High post-fire regrowth	10.7379	13.4451	15.678	12.2373	10.1835
Low post-fire regrowth	38.2059	52.8687	52.533	55.6461	44.5545
Unburned	290.8539	350.3628	348.2262	362.3787	341.3403
Low-severity burn	102.6819	99.5607	102.51	90.4995	116.1675
Moderate- to low- severity burn	62.9478	21.5685	19.3302	18.1386	24.1542
Moderate- to high-severity burn	28.9071	5.4144	4.6863	4.4154	6.8031
High-severity burn	9.3123	0.1971	0.1854	0.1836	0.3456

In order to observe the evolution of burn severity in the affected area over time, the Differenced Normalized Burn Ratio (ΔNBR) was calculated between the pre-fire data set acquired in 2017 and the five post-fire data sets acquired between 2017 and 2021. Fig. 6 shows the evolution of ΔNBR in the analyzed area over five years.

As shown in Fig. 6, in 2017, when this forest fire occurred, areas with a low-severity burn (colored in yellow) and moderate- to low-severity burn (colored in orange) were predominantly observed. Although affected areas with moderate- to high-severity burn (colored in red) and high-severity burns (colored in violet) were present, however, were not predominant. In the following four years, the predominant categories observed are low post-fire regrowth (colored in light green) and low-severity burn (colored in yellow). Besides, there is a minimal presence of pixels colored in orange and red that still show a moderate- to low- and moderate- to high-severity burn.

Table 7 presents the calculation of the ΔNBR for each of the years analyzed and its distribution in the seven different burn severity categories.

As shown in Table 7, analyzing the low post-fire regrowth category, there is an increase of 16.62%, considering that in 2017 covered 38.2059 km², and for 2021 it rises to 44.5545 km². In addition, analyzing the moderate- to low-severity burn category, there is a reduction of 61.63%, considering that in 2017 covered 62.9478 km², while in 2021, it dropped to 24.1542 km². Moreover, analyzing the moderate- to high-severity burn category, there is a reduction of 76.47%, since in 2017 covered 28.9071 km², and in 2021 covered 6.8031 km². Finally, analyzing the high-severity burn category, there is an area of 9.3123 km², while for 2021, the covered area drops to 0.3456 km², which means a reduction of 96.29% for this category. Therefore, having obtained these results, it can be verified that there is a favorable evolution in the area affected by the forest fire since the categories that show burn severity in the area have registered a decrease in the last five years, while the categories that show regeneration of vegetation have registered an increase.

5. Conclusion

Cordillera de Sama Biological Reserve is an important natural area for Bolivia because it is home to a wide diversity of flora and fauna. It also comprises three ecoregions and has various hydrographic basins, as this reserve effectively regulates water flows. That is why when this biological reserve was affected by a large-scale forest fire on August 8, 2017, it was a national concern, as could be seen in the results obtained from the calculation of the Normalized Burn Ratio (NBR) during this forest fire, 122.1471 Km² were affected, which means 11.26% of the total area of this biological reserve. It is essential to mention that the total burned area calculated by the NBR index is approximately equivalent to Dublin city, the capital of the Republic of Ireland, which has a total area of 117.8 km². Given the ravages of this forest fire, local authorities proposed different reforestation plans for the burned area [56, 57].

The present study develops a damage assessment evaluating the degree of affectation and subsequent recovery of the area affected by the fire to observe the evolution of burn severity in the affected area over time. Landsat 8 satellite was used to analyze pre-fire and post-fire satellite imagery from 2017 to 2021. Six data sets were analyzed, one pre-fire image, acquired 25 days before the forest fire in the area, and five post-fire images, acquired from 2017 to 2021. It should be noted that the first post-fire image, corresponding to the year 2017, was acquired only two days after the end of the fire.

In order to measure the degree of affectation and to develop a subsequent recovery analysis of this forest fire in the study area, two burn indices were calculated: the Normalized Burn Ratio (NBR) and the Normalized Burn Ratio - Thermal (NBRT1) and their evolution during five years from 2017 to 2021. NBRT1 index was calculated since it provides greater accuracy in the separability of the burned and unburned area by using thermal bands. From this analysis, it was possible to observe that, according to the NBR index, the burned area in 2017 covered 122.1471 Km² of the Cordillera de Sama. Whereas in 2021, it covered only 17.2494 Km², which means a recovery of 85.88%, and even in 2020, the burned area only covered 10,6434 km², possibly the increase recorded in 2021 is due to some minor burning (chaqueo) in the area. According to the NBRT1 index, the affected area in 2017 covered 114.2352 km². In 2021, it covered only 29.5488 km², which means a recovery of 74.13%. Even in 2020, the burned area only covered 23.8284 km²; again, the increase registered for the year 2021 may be due to a chaqueo in the area.

Besides, to identify areas that have been more affected due to the fire and its evolution over five years, the Differenced Normalized Burn Ratio (ΔNBR) was computed using the pre-fire and post-fire data sets for calculating the absolute change in the NBR. As a result, maps were obtained to observe the different levels of burn severity and the levels of regrowth and its evolution in the Cordillera de Sama Biological Reserve from 2017 to 2021. This analysis found that in the category of low post-fire regrowth, there was a variation from 7.03% to 8.20%. Besides, there was a variation from 11.58% to 4.44% in the moderate- to low-severity burn category. In addition, in the moderate- to high-severity burn category, there was a variation from 5.32% to 1.25%. Finally, there was a variation from 1.71% to 0.06% in the high-severity burn category. These variations recorded from 2017 to 2021 are indicators that evidence the recovery of the area affected by this forest fire.

Remote sensing is a crucial tool for the three stages of a forest fire: initiation, propagation and extinction of the fire, as it provides crucial information on the area affected by the fire that is helpful to the authorities and actors who carry out work on the ground. However, this technology has certain limitations. For example, in this case, when using the Landsat 8 satellite, an optical satellite, it was necessary to avoid analyzing data sets with cloud cover greater than 20%.

In future work, it is desired to implement a system that supports authorities for the fire risk assessment and damage assessment, as well as for monitoring active fires. This system is relevant because when a disaster of the magnitude of a forest fire occurs, the authorities - whether local or national - need to make quick decisions to mitigate the fire and regenerate the affected area, yet, these decisions must be made based on well-founded information.

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