

Assessment of Post-Fire Regeneration in the Mesguina Forest (Morocco) Using Remote Sensing and GIS

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Abstract

This study aims to quantify the area affected by the 2013 wildfire in the Mesguina Forest in Morocco and monitor vegetation regeneration over six years (2013–2019) using remote sensing and GIS. A spatio-temporal database was created using Landsat-8 and Sentinel-2 imagery, which was supplemented by field observations. Two spectral indices were employed: the Normalised Difference Vegetation Index (NDVI) to evaluate vegetation coverage and density, and the Normalised Burn Ratio (NBR) to precisely delineate burnt areas. Satellite images acquired before and after the fire were processed using ArcGIS, ENVI, SNAP and QGIS software. The NDVI and NBR results were then classified in order to quantify changes in vegetation cover. The NDVI and NBR analyses revealed that 49.3 % (958 ha) to 54.85 % (1,066 ha) of the forest was burnt in July 2013. The most severe degradation occurred by 2015, leaving extensive areas of bare and degraded soil. Thereafter, gradual

regeneration was observed, mainly on northern slopes and near river systems, dominated by regrowth of the species *Tetraclinis articulata*. By 2019, the regeneration rate had reached 58.48 % (560 ha of the burnt area). However, the analysis relies on medium-resolution satellite imagery, which may overlook fine-scale regeneration patterns. Furthermore, the study is limited to six years post-fire and does not assess long-term successional dynamics. Nevertheless, this study provides the first quantitative evidence of post-fire regeneration dynamics in a semi-arid Mediterranean forest in Morocco. By combining NDVI and NBR, it demonstrates the spatial heterogeneity of recovery and the strong influence of slope orientation and water proximity. These ecosystem-specific patterns, not previously documented in the Mesguina forest, differ markedly from those reported in temperate and boreal forests, offering valuable spatial data for post-fire management and monitoring.

Keywords: Aridity, disturbance ecology, NBR, NDVI, semi-arid ecosystems, slope orientation

Introduction

Moroccan forests, which cover approximately 12 % of the country's total land area, play a crucial role in biodiversity conservation, climate regulation, and the provision of essential ecosystem services, such as timber production, soil protection, and groundwater recharge (INRA 2017). These forests consist of 78 % deciduous trees (including holm oak, argan tree, cork oak, and Saharan acacia) and 22 % coniferous species (such as cedar, *Thuja*, pine, juniper, cypress, and fir) (Ahlafi 2014, DEF – BA 2018). These softwood forests are particularly susceptible to fire outbreaks (HCEFLCD and US Forest Service 2013, Ellatifi 2014, HCEFLCD 2016). However, these ecosystems face multiple challenges, including increasing aridity due to climate change, growing anthropogenic pressures, and agricultural expansion, all of which contribute to ecological fragility (Hajib 2013).

Significant advances have been made in the use of remote sensing and GIS for monitoring forest ecosystems after fires over the past two decades (Key and Benson 2006, Chuvieco et al. 2019). These tools enable the accurate quantification of burnt areas, tracking of regeneration dynamics and identification of environmental factors influencing recovery. However, most existing studies focus on temperate or boreal forests, with very few addressing the semi-arid Mediterranean forests of Morocco, which are under significant climatic and anthropogenic pressure. The limited research conducted in this context has mainly focused on the argan forest or fire prevention measures, without providing a long-term quantitative assessment of post-fire

regeneration. This hinders our comprehensive understanding of the mechanisms and pace of vegetation recovery in these environments.

Forest fires are one of the primary factors contributing to the degradation of natural ecosystems worldwide. Fire is recognised as a natural phenomenon that plays a crucial role in numerous terrestrial ecosystems, significantly influencing their distribution, structure, and evolutionary processes (Ireland and Petropoulos 2015). Indeed, recurrent fires in forested areas are a major disturbance that can profoundly affect vegetation dynamics, structure, and regeneration (Sathya and Jayakumar 2017). In Morocco, this phenomenon poses a growing threat to forest resources, exacerbated by climate change and increased human activity (HCP 2020, CRS 2025). However, recurrent fires, whether natural or anthropogenic, severely disrupt vegetation cover. These disturbances not only affect the composition and structure of forests but also hinder their ability to regenerate, with potentially irreversible consequences for ecosystems and the communities that depend on them (INRA 2017).

Forest fires remain a recurrent threat, destroying thousands of hectares annually in Morocco. Approximately 50,000 fires affect between 700,000 and 1,000,000 ha each year, with causes that are largely unknown (55 %), accidental (37 %), or deliberate (8 %) (Mhirit 1996, HCEF 2020, Colin et al. 2001). To address this issue, the High Commission for Water, Forests, and Desertification Control (Lhafi 2013), in partnership with the Government of Andalusia, launched a Master Plan for Forest Fire Prevention and Management in 2001. This 20-year programme integrates legal, environmental, and socio-economic measures to enhance the resilience of forest ecosystems (HCEFLCD and US Forest Service 2013).

In the Souss-Massa region, forests cover more than 1.16 million hectares, representing 13 % of the national forest area in 2020, compared to 19.1 % in 1997. The argan forest, with *Argania spinosa* L. as its emblematic species (Rammal et al. 2009), spans 730,127 ha, including 220,559 ha in the Agadir-Inzegane-Chtouka area (DEF – BA 2018) and 13,672 ha in Amsekroud (MAPMDREF and INRA 2013, 2017). In addition to its ecological functions, the forest serves as an important barrier against desertification and erosion caused by wind and water.

The Amsekroud fire, which occurred in the Mesguina forest, destroyed 1,625 ha of vegetation (Irifi et al. 2018) and more than 1600 ha (Irifi et al. 2025). The primary objective of this article is to precisely determine the burnt areas in the Mesguina forest using the Normalized Burn Ratio (NBR) in addition to the NDVI in 2013, and to monitor the forest regeneration within the burnt areas between 2013 and 2019 using the NDVI.

Despite progress in post-fire monitoring, studies in Morocco have mainly focused on mapping burnt areas and general regeneration trends,

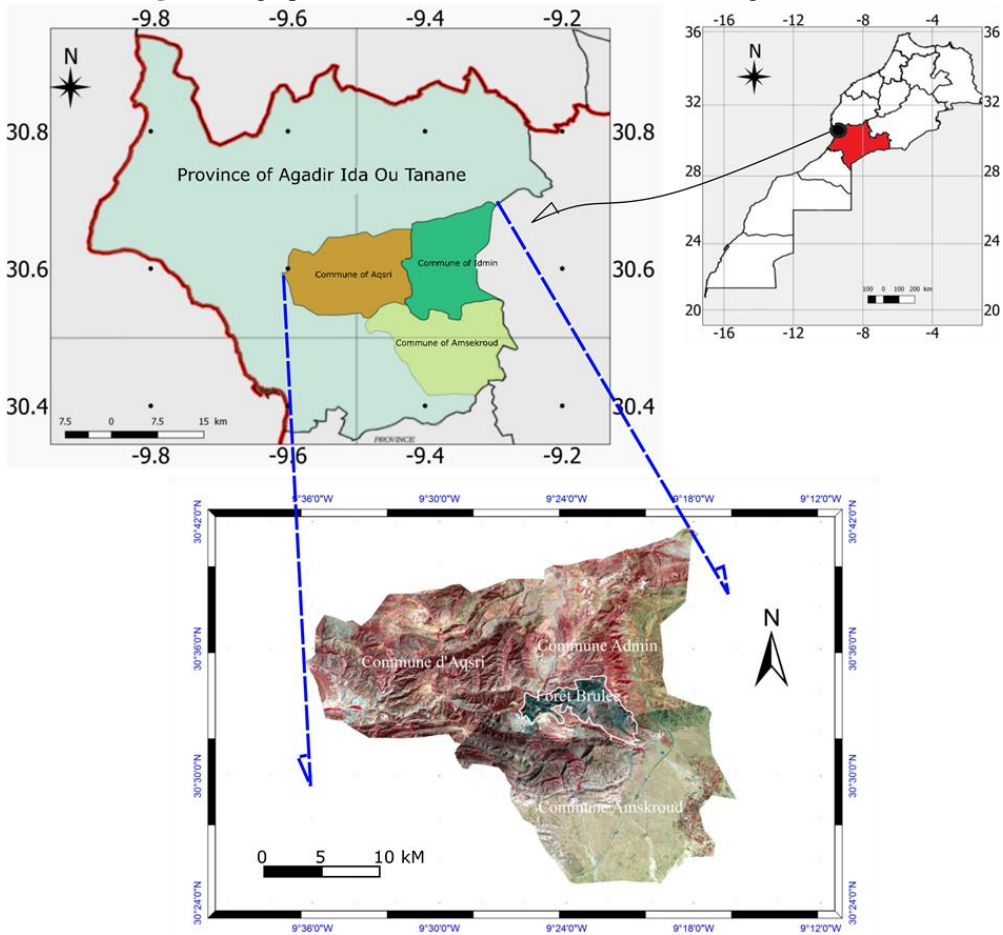
neglecting topographic and hydrological influences. No detailed research has examined how slope orientation or proximity to watercourses affect regeneration in the Mesguina forest. This study fills that gap through six years of spatio-temporal monitoring after the 2013 fire, providing new quantitative data on burnt area extent, regeneration rates, and spatial patterns. It tests the hypothesis that regeneration is spatially heterogeneous and shaped by these factors, aiming to enhance understanding of post-fire dynamics and guide management in semi-arid Mediterranean ecosystems.

Materials and Methods

Description of the study zone

The study area is situated in the Mesguina forest estate, within the province of Agadir Ida Outanane. This province forms part of the Souss-Massa region. The Mesguina forest spans 108,361 ha and is located in the south-west of Morocco. It is bounded by the Atlantic Ocean to the west and the foothills of the Western High Atlas to the north. The forest lies on a narrow continental plateau that opens onto the Souss Massa plain. This forest is classified within the semi-arid bioclimatic zone, characterised by warm winters and high annual humidity (73 %), which compensates for the low rainfall, particularly during the summer months, when humidity levels reach 76 to 78 %. The area is occasionally exposed to east winds (Chergui), which lead to elevated temperatures between late spring and mid-autumn.

Fig. 1: Geographical location of the burnt area in the Mesguina forest



Note: The detailed map below illustrates the boundaries of the burnt area, highlighted by a white line.

Administratively, the forest falls under the jurisdiction of the Souss-Massa region, within the Agadir Ida Outanane prefecture, and encompasses several communes: Drarga, Ameskroud, Idmine, Akesri, Aourir, Ouled Dahou, and the urban community of Agadir (Es-siari 2016).

The area affected by the fire spans between the geographical coordinates ($9^{\circ}21'0''$ N and $9^{\circ}26'5''$ N / $30^{\circ}31'5''$ W and $30^{\circ}34'5''$ W), at the intersection of the three communes of Ameskroud, Akesri, and Idmin. The burned forest is situated on the southern flank of the Western High Atlas, within a section of the Mesguina forest, approximately 25 km north-east of Agadir.

Data sources

The study adopted an approach based on the analysis of satellite data acquired before and after the fire, validated through field checks. The assessment of the fire's impact was conducted using remote sensing and GIS to analyse Landsat-7 and Landsat-8 (USGS 2020) and Sentinel-2 (ESA 2020) satellite images acquired on 31 July 2013, 16 August 2013, 12 July 2015, and 28 August 2019. This approach enables a comparison of the satellite data with the actual conditions on the ground, thereby enhancing the accuracy of the analyses and interpretations.

The digital data used in this study comprise several types, including the Digital Elevation Model (DEM) and spectral bands from Landsat-7, Landsat-8, and Sentinel-2 (Table 1).

Table 1: Characteristics of the spectral bands used (ESA 2020)

Image ID	Satellite and sensor	Acquisition dates	Spatial resolution	Number of bands
LC82030392013212LGN01	Landsat-8 OLI/TIRS	31 July 2013 16 August 2013 28 August 2019	30 m (B1–B7 and B9); 100 m (B10 and B11); 15 m (B8)	11
S2A_OPER_MSI_L1C_DS_M TI_N0204_R137_T29RMP	Sentinel-2 MSI	12 July 2015	60 m (B1, B9, B10); 20 m (B5–B8a, B11 and B12); 10 m (B2–B4 and B8).	13

Several GIS software packages were used in this study, including ArcGIS, ENVI 4.5, SNAP, Global Mapper, and QGIS 2.16.3.

The Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) instruments on board the Landsat satellites capture multispectral images. The OLI provides 9 spectral bands, including two new bands designed for atmospheric correction and cloud detection. The TIRS measures thermal infrared radiation, continuing observations initiated by earlier satellite missions. Additionally, the Sentinel-2 satellites, launched in 2015 and 2017 as part of the Copernicus programme, deliver high-resolution optical data for environmental monitoring, land-use analysis, and emergency management.

The study commenced with the collection and acquisition of digital data to delineate the burned area. The satellite images were pre-processed prior to analysis. Standard procedures described by USGS (2020) and ESA (2020) were applied for atmospheric correction and radiometric calibration to Landsat-8 OLI/TIRS and Sentinel-2 MSI data. Each image was subsequently georeferenced and clipped to the boundaries of the study area. For this purpose, Landsat-8 satellite bands acquired shortly after the fire on 16 August 2013 were used. An RGB 5-4-3 band composition was employed to generate a bi-temporal composite image comparing the pre-fire (31 July 2013) and

post-fire (16 August 2013) conditions. The use of GIS software for georeferencing, digitisation, and mapping enabled the creation of a burnt-area map (Fig. 1).

The selection of appropriate spectral bands, as well as the determination of the most suitable seasons and months, is critical for image acquisition and resolution definition. For this study, Landsat-8 images acquired between 2013 and 2019 during the months of July, August, and September were selected.

The subsequent phase involved the processing of the acquired data. Two primary indices were calculated in this study: the Normalised Difference Vegetation Index (NDVI; Rouse et al. 1973) and the Normalised Burn Ratio (NBR; Key and Benson 2006). NDVI was used to assess vegetation cover and density, while NBR was used to identify burnt areas. The mathematical expressions used to compute these indices are as follows:

$$NDVI = \frac{NIR-R}{NIR+R} \tag{1}$$

calculated from two spectral bands: red (R) and near-infrared (NIR);

$$NBR = \frac{NIR-SWIR_2}{NIR+SWIR_2} \tag{2}$$

calculated from near-infrared (NIR) and shortwave infrared (SWIR₂) spectral bands.

To facilitate interpretation, the NDVI and NBR results were classified into discrete categories. NDVI values were grouped into five vegetation classes: degraded soil, bare soil, sparse forest, dense forest, and very dense forest. NBR values were classified as burnt or unburnt using threshold values adapted from Key and Benson (2006). These classifications were subsequently used to produce thematic maps for each acquisition date, enabling step-by-step visualisation of changes in vegetation cover and fire-affected areas between 2013 and 2019. To evaluate the reliability of the NDVI classification, an accuracy assessment was performed using reference points collected from field observations and high-resolution imagery from SAS planet software. A confusion matrix was generated and two indicators were calculated: Overall Accuracy (OA) and Kappa coefficient.

Table 2 : Statistics of NDVI class area evolution between 2013 and 2019 in the burnt area, in ha

	Degraded soil	Bare soil	Sparse forest	Dense forest	Very dense forest	Total
Degraded soil	18	2	0	0	0	20
Bare soil	1	21	2	0	0	24
Sparse forest	0	2	17	1	0	20
Dense forest	0	0	2	16	2	20
Very dense forest	0	0	1	2	17	20

The classification achieved an Overall Accuracy of 87,6% and a Kappa coefficient of 0.84, indicating a high level of agreement between classified and reference data.

Following Key and Bensen (2006), NBR values were classified into burned and unburned categories. Pixels with NBR values lower than 0.10 were considered burned, whereas pixels with values greater than 0.10 were classified as unburned. The threshold was adjusted through visual inspection of post-fire imagery.

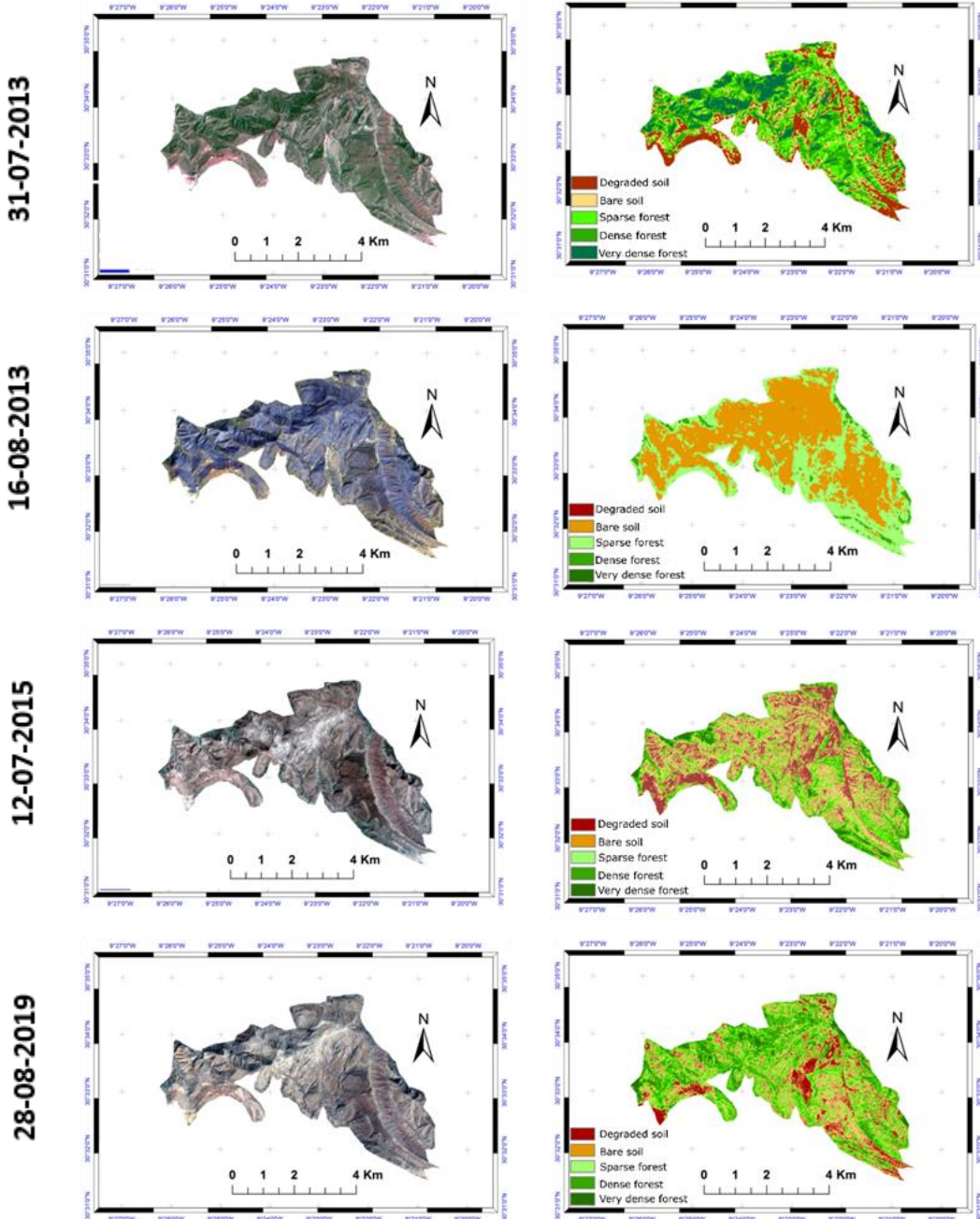
Results

Vegetation cover changes using NDVI index

The data calculated for the NDVI index reveal a significant disparity in living vegetation cover between 2013 and 2020. The statistics were derived from the classification of NDVI values into five distinct vegetation classes: degraded soil, bare soil, sparse forest, dense forest, and very dense forest.

The original satellite images (Landsat-8 OLI/TIRS for 2013 and 2019, Sentinel-2 MSI for 2015) were processed to delineate the burnt area. Burnt-area boundaries are highlighted to indicate the spatial extent of the study site. These data were subsequently used to produce thematic NDVI maps for each acquisition date, enabling step-by-step visualisation of changes in vegetation cover and fire-affected areas between 2013 and 2019 (Fig. 2).

Fig. 2 : NDVI maps for burnt area between 2013 and 2019

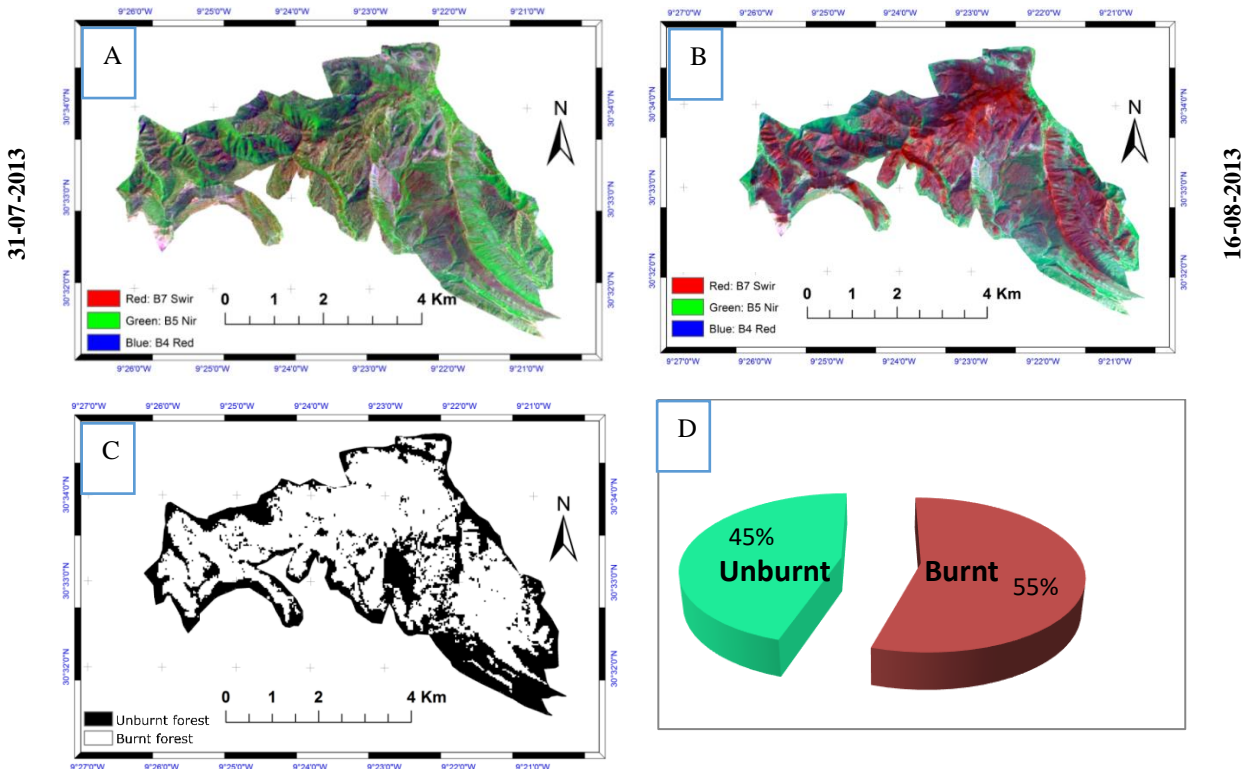


Note: Satellite images were acquired on 31 July 2013, 16 August 2013, 12 July 2015, and 28 August 2019. The colour scale represents vegetation density, from degraded soil (brown) to very dense forest (dark green). Burnt-area boundaries are outlined in white. The maps illustrate vegetation degradation after the July 2013 fire and subsequent regeneration up to 2019. Images were obtained from Landsat-8 OLI/TIRS and Sentinel-2 MSI via USGS (2020) and ESA (2020).

Burnt area mapping using NBR index

Bi-temporal NBR maps were produced from Landsat-8 bands B5 and B7, after pre-processing reflectance using solar elevation. NBR values were classified into two categories: black for unburnt area and white for the burnt areas. The resulting maps allow step-by-step visualisation of the burnt-area extent (Fig. 3).

Fig. 3 : Representation of burnt area with panels showing (A) satellite map, (B and C) NBR index maps, and (D) statistical data



Note: Black areas indicate unburnt vegetation, white areas represent burnt zones, and burnt-area boundaries are outlined in red. NBR was calculated following Key and Benson (2006), with classification thresholds applied. Maps illustrate fire-affected areas before and after the July 2013 fire.

Discussion

Regeneration was assessed by comparing the results obtained over the 2013–2019 study period. The state of regeneration is presented in Table 2 and Figure 4.

Table 3 : Statistics of NDVI class area evolution between 2013 and 2019 in the burnt area, in ha

Date	Area, ha					
	Degraded soil	Bare soil	Sparse forest	Dense forest	Very dense forest	Total forest area
31.07.2013	85.05	388.40	366.55	611.84	964.72	1943.06
16.08.2013	0.06	1430.88	897.08	87.90	0.11	985.09
12.07.2015	588.52	947.69	542.34	242.13	96.27	880.74
28.08.2019	306.91	727.42	753.92	485.29	144.16	1383.37

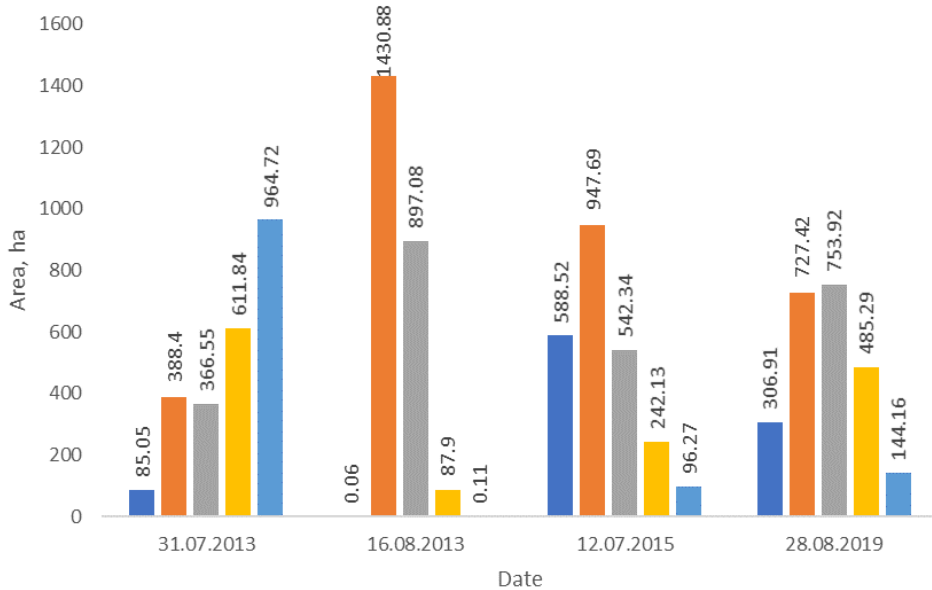
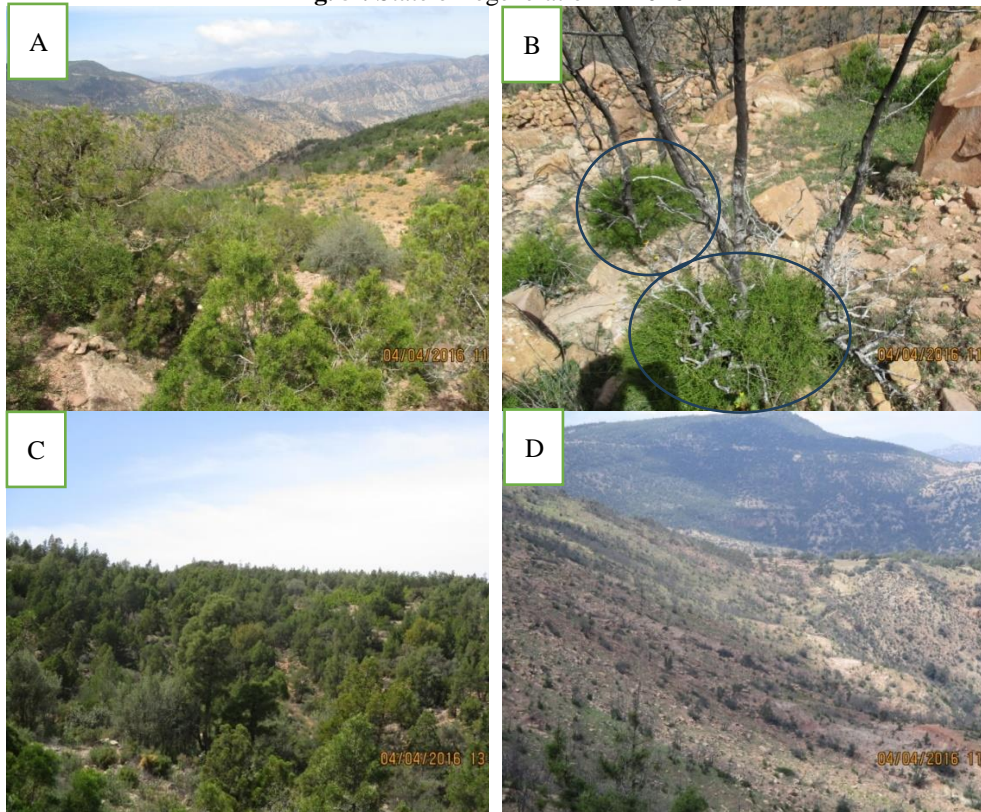


Fig. 2 : Graphical representation of the evolution of NDVI class areas between 2013 and in the burnt area

Between 31/07/2013 and 16/08/2013, the vegetation cover underwent massive degradation as a result of the fire, followed by gradual regeneration between 16/08/2013 and 28/08/2019. The two forest classes, dense and very dense forest, regressed in favour of bare soil, while the sparse forest class expanded due to the creation of gaps between the trees of the other forest classes. This has exposed a very large area of soil to erosion and mass movements (landslides, slides and collapses), particularly as a result of hydric erosion. In this case, the carbonate nature of the terrain means that steep cliffs can form, which, when deforested, promote gravitational soil movement. In fact, in 2015, the area of degraded soil increased due to erosion. The degradation of vegetation cover facilitated the action of erosive factors on bare soil and has allowed the establishment of a hydrographic network that increased the surface area of degraded soil. Photographs taken in 2016 show

that regeneration has begun, especially of *Tetraclinis articulata* (Vahl) Mast. (Fig. 5).

Fig. 5 : State of regeneration in 2016



Note: (A) regeneration in empty spaces; (B) new recovery of cedar (see circles in the image); (C) new recovery of holm oak and cedar in empty spaces; (D) cedar regeneration according to exposure.

In 2019, average regeneration of the forest vegetation cover was observed, concentrated on the N and NE slopes, near the summits (carbonate bars) and in the vicinity of the hydrographic network. Compared with the state of the forest before the fire on 31 July 2013, regeneration is not homogeneous throughout the study area. Analysis of the NDVI index shows that the recovery of *Tetraclinis articulata* was significant compared with other species. Calculations carried out in the burnt area (B in Fig. 1) show that the surface area of burnt vegetation in this area amounts to 957.97 ha, or 49.3 %, and that the plant regeneration rate in the same area is 58.48 %, corresponding to a surface area of 560.23 ha. The NBR fire index also enabled us to calculate the surface area of burnt vegetation in our burnt area. According to these results, 54.85 % of the area occupied by vegetation in the burnt area was burnt, i.e. 1,065.75 ha. The difference between the results of the NDVI and NBR indices

for the burnt area is explained by the fact that the NBR index takes into account burnt leaves and branches, as well as bare soil displaced by wind.

The spatial heterogeneity of post-fire regeneration observed in the Mesguina forest can be explained by the influence of topographical and hydrological factors, notably slope aspect and proximity to watercourses. Indeed, the aspect of the slopes has a significant influence on water availability, soil temperature and local microclimatic conditions. In the Northern Hemisphere, north-facing slopes receive less intense solar radiation. They therefore retain higher moisture levels and experience more moderate temperatures. These climatic conditions favour the germination and development of young seedlings. In contrast, south-facing slopes receive increased sunlight, leading to higher evapotranspiration and more pronounced water stress. This situation limits the density and speed of post-fire vegetation regeneration.

Furthermore, the proximity of wadis, thalwegs and other watercourses is a factor conducive to plant recolonization. It has been demonstrated that these areas offer significant advantages in terms of water availability, soil depth and nutrient richness, as well as a less harsh microclimate. Furthermore, these features can facilitate seed dispersal through runoff or the action of wildlife. Indeed, in the post-fire context, areas adjacent to watercourses frequently become centres of rapid regeneration.

As indicated in the report, the combined effect of these parameters explains the spatial variability in regeneration dynamics observed in Mediterranean and semi-arid ecosystems. Areas on north-facing slopes and near water sources demonstrate superior and faster regeneration capacity, whilst south-facing areas distant from watercourses show slower and more limited vegetation recovery. This interaction between topography, water availability and microclimate is a key factor to consider in analysing the post-fire resilience of the Mesguina forest.

The result obtained in this study are generally consistent with those reported by Irifi et al. (2025). However, important methodological differences distinguish the two studies. The present study employed a combined NDVI-NBR approach to quantify both burned areas regeneration dynamics over six years (2013-2019) focusing on the state of regeneration in 2019, 957.97 ha using NDVI to 1065.75 ha using NBR within the investigated perimeter. In addition, this study quantified a regeneration rate of 58.48% (560 ha), providing a numerical assessment of vegetation recovery that complement the quantitative observations reported by Irifi et al. (2025). Furthermore, this study highlights the influence of environmental factors on post-fire regeneration dynamics. The results show that vegetation recovery was more pronounced in area located near the hydrographic network and on north and northeast slopes. These sectors benefit from more favourable microclimatic

conditions, including higher soil moisture, lower germination and seedling establishment. In contrast, south-facing slopes, which receive greater solar exposure, experienced slower regeneration due to increased water stress. The spatial distribution of fire damage also appears to be strongly influenced by topography, slope exposure, the hydrographic network, prevailing winds, and vegetation composition. Regeneration was more pronounced near watercourses and on north-facing slopes. In contrast, summer winds and the presence of highly flammable species, particularly *Tetraclinis articulata*, contributed to fire spread and severity on exposed slopes. These results highlight the important role of topographic and ecological factors in post-fire regeneration dynamics.

Conclusions

The study evaluated the condition of the area affected by the 2013 fire in the Amsekroud region and monitored plant regeneration in the area. Between July and August 2013, a fire severely degraded the vegetation cover in the study area, followed by gradual regeneration until 2019. The NDVI index was used to monitor forest regeneration, while the NBR index proved indispensable for calculating burnt areas, particularly when combined with NDVI index. The present study successfully quantified post-fire regeneration in the Mesguina forest over a six-year period. This demonstrated that recovery is heterogeneous rather than uniform across the landscape. It provides the first quantitative evidence in Morocco that slope orientation and proximity to hydrographic systems significantly influence regeneration dynamics in the Mesguina forest. This fills a critical gap in regional research, as these environmental drivers had not previously been investigated. Beyond its scientific contribution, the study paves the way for applying similar approaches to other semi-arid ecosystems, and for integrating topographic and hydrological parameters into forest management and restoration strategies.

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Data Availability: All data are included in the content of the paper.

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