ASSESSMENT AND MONITORING OF POST-FIRE RECOVERY USING SATELLITE IMAGERY AND THE STABILITY INDEX IN THE NORTH WEST OF ALGERIA

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Abstract:

Forest fires are a complex natural phenomenon, difficult to model because they depend on many parameters, which vary in both time and space. It is therefore necessary to carry out research and prevention actions as part of the improvement and management of this risk. The severity of wildfires due to hotter and drier global climate conditions affects the ecological resilience and ecosystems at risk of deterioration following the failure of post-fire recovery. To properly prepare for wildfires, it is crucial to determine fire-sensitive areas, then locate fire suppression structures, and assess the spatial and temporal quantification of post-fire regeneration. The objectives of this study are, in the first stage, the fire detection using remote sensing and GIS, and in the second stage, to model the dynamics of regeneration and monitor the recovery of vegetation using satellite imagery and the post-fire stability index. This method is therefore based on the concept that the state of a disturbed system will be reflected by increasing or decreasing rates of change. While undisturbed or recovered system states are characterized by rates of change close to zero. This reflects the typical pattern of decreasing change rates in post-fire recovery trajectories. To do this, time series analyses of remote sensing images from Landsat satellite between 2013 and 2020, both pre- and post-fire, were conducted in the Sidi Bel Abbés region, Algeria, and for the post-fire stability index, we used NBR and NBR2 as the base spectral indices to evaluate the post-fire stability index. Moreover, the rate of vegetation recovery after a fire was then assessed using the normalized regeneration index. (NRI). We therefore demonstrate the performance and relevance of the post-fire stability index compared to alternative approaches because this stability index provides a relatively simple and practical solution for consistent large-scale monitoring of post-fire recovery with satellite imagery, which, combined with standardized mapping of fire severity, thus offers numerous opportunities for further research on fires, forest recovery, and landscape ecology.

1. Introduction

Among the various factors that threaten forests in the Mediterranean region, and more particularly in Algeria, forest fires constitute the most devastating factor of degradation. Their intensity and brutality cause considerable losses, affecting vast areas of forest and pre-forest areas in relatively short periods of time. Wildfires, or wildfires, are disasters that occur in vegetation formations dominated by forest trees and shrubs. These fires can also occur in sub-forest formations, such as maquis (dense, closed vegetation growing on siliceous soil) and garrigue (more open vegetation, typical of calcareous soils). A forest fire is defined as a fire affecting an area of at least one hectare, in a single block, and with a minimum width of 25 meters. Algeria's already fragile forests require urgent protection as deforestation continues to increase, particularly due to recurring forest fires. Between 1990 and 2020, forest fires ravaged the equivalent of 779,872.11 hectares, with a total of 32,354 recorded outbreaks, resulting in significant ecological and economic consequences.

Most Mediterranean plant species exhibit effective regeneration mechanisms for overcoming the immediate effects of fire. Plant species mechanisms can be passive or active, which may lead to a rapid process of vegetation cover (Perez-Cabello et al. 2009). However, the response of vegetation to fire is very complex and it is not easy to generalize because of the large number of factors that can affect the regeneration process (climatic influences, plant composition, topographic parameters, soil characteristics, etc.). Fire has become increasingly important in the Mediterranean and many other ecosystems, due to recent land-use and climatic changes (Pausas, 2004). Pinus halepensis (Aleppo pine), together with the closely related Pinus brutia, are the most widespread trees in the Mediterranean Basin. Forest fires, when they are not frequent, promote the extension of conifers (Quezel, 1980). Note that the natural regeneration of the conifer forests in Mediterranean mountain, such as the cedar, is often consecutive to the emergence of fires, as shown locally the predominance of forest stands even-aged. Every year there are more than 1,000 forest fires in Algeria, affecting over 25,000 ha of forest and other woodland, the majority occur in the North. Although fire is a natural process of Mediterranean ecosystems (Chuvieco 1997,Trabaud et al. 1980). Spatial databases on forest fires are necessary to support fire Management programs and evaluate the manifold implications of fire occurrence (Koutsias et al. 1999).
Assessing the dynamics of natural regeneration and post-fire recovery, particularly in large areas, now increasingly requires data covering vast spatial extents over multiple time steps. Remote sensing therefore offers a viable and cost-effective solution for identifying and capturing observations of post-fire recovery dynamics.

Post-fire forest dynamics have been characterized by several satellite-derived spectral vegetation indices, which contrast short-wave infrared (SWIR) and near-infrared (NIR) wavelengths, such as the normalized burn rate (NBR). Hence, post-fire forest dynamics (e.g., fire severity and recovery) have strong correlations with field measurements (Gibson et al., 2020; Hislop et al., 2018; Kennedy et al., 2010; Shvetsov et al., 2019; White et al., 2017; Wulder et al., 2009). Comparing NBR changes with pre-fire NBR (RdNBR) improves accuracy, particularly for higher severity classes in heterogeneous landscapes (Miller et al., 2009; Miller and Thode, 2007). Several studies on the use of optical remote sensing for monitoring post-fire spectral forest regeneration have demonstrated that SWIR-based indices exhibit greater sensitivity to the impacts of fire on forest canopy and canopy structure regeneration, indicating their relevance for monitoring progressive canopy recovery (Cuevas-Gonzalez et al., 2009; Schroeder et al., 2011). A study from Southern California (Storey et al., 2016) showed that the modified version of the NBR, which compares two SWIR wavelengths (NBR2), has recently gained interest, with promising results for assessing post-fire vegetation regeneration.

We based this work on the work that was carried out by Rebecca K. Gibson et al, 2022), whose objective was to use NBR and NBR2 as basic spectral indices to develop the Post-Fire Stability Index. The formula of the Post-Fire Stability Index follows the structure and scaling of the widely used Relativized Differenced Normalized Burning Rate (RdNBR; Miller and Thode, 2007), which is generally applied to pre- and post-fire images to assess the immediate post-fire impact. However, we adapted this concept to assess ongoing post-fire effects through a continuous sequence of differencing images taken on multiple dates, since post-fire forest regeneration in the Mediterranean is slow. The Post-Fire Stability Index was compared with NDVI Normalized Vegetation Index differentiation methods. Candidate methods were generated by the following equations:

$$\boldsymbol{NBR} = \frac{\mathrm{NIR-SWIR2}}{\mathrm{NIR+SWIR2}} \qquad (1)$$

$$\boldsymbol{NBR2} = \frac{\mathrm{SWIR1-SWIR2}}{\mathrm{SWIR1+SWIR2}} \qquad (2)$$

$$\boldsymbol{PFSI: NBR2\ Postfire\ Stability\ Index} = \frac{(NBR2\ at\ Time\ t - NBR2\ at\ Time\ \ 1)}{\left(sqrt\left(ABS\left(\frac{NBR2\ at\ Time\ \ 1}{1000}\right)\right)\right)} \qquad (3)$$

The NDVI (Normal Difference Vegetation Index), developed by Rouse et al. (1974) is, without doubt, the index most widely used in various applications of remote sensing, including evaluation of the process of regeneration post-fire (Henry and Hope, 1998; Viedma et al., 1997):

$$\textbf{NDVI} = (PIR - R) / (PIR + R) \qquad (4)$$

2. Main objective and study area

The objective of this study is monitoring vegetation recovery after fire by using remote sensing data and the stability index. This study aims to analyze post-fire vegetation recovery as a temporal and spatial process with series of images (2013, 2014, 2016, and 2020).

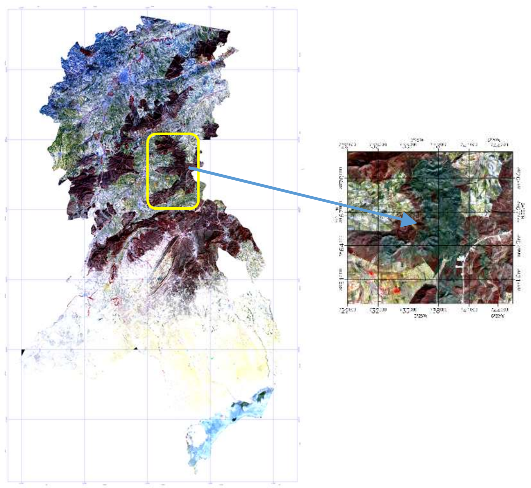

Figure 1. Location of the study area

3. Materials and Methodological approach

It is worth recalling that the aim of this work is to assess and quantify spatio-temporal variation and vegetation recovery within a burnt area through a diachronic analysis of remote sensing data and using a derived index, coupled with field observations.

This analysis involves assessing the regrowth recovery of different plant species and studying different spatial patterns of regeneration. We studied and analyzed different techniques for monitoring vegetation recovery after fires, but in this work, only the results obtained using the NDVI vegetation index, the NBR index, and the NBR2 post-fire stability index will be presented.

This work was carried out in an area located in the Sidi Bel Abbés region, in northwest Algeria, where a major forest fire occurred during the 2014 summer season. This area was occupied by a mixed forest of cedar (Tetraclunis articulata), a species endemic to North Africa, and Aleppo pine (Pinus halepensis).

3.1 Datasets

The study was carried out on images Landsat acquired in 2013, 2014, 2016 and 2020 to evaluate forest regeneration (Table 1).

Table 1. Characteristics of satellite images used in the study

Image	Dates Acquisition	Band Number	Spectral Wave	Spatial Resolution
Landsat 8 Oli	30-09-2013 31-07-2014 01-09-2014 06-09-2016 01-09-2020	Band 2	0,45 - 0,51	30 m
		Band 4	0,64 - 0,67	
		Band 5	0,85 - 0,88	
		Bande 6 (SWIR 1)	1,57 - 1,65	
		Band 7 (SWIR 2)	2,11 - 2,29	

3.2 Treatments

In this study, we applied the NBR index to the 2014 Landsat image to assess the fire area. The application of the Normalized Burn Ratio (NBR) index provides significant benefits in the automatic extraction of burned areas. It is an index designed to highlight burned areas within large fire zones. The value range is from -1 to 1. A high NBR value indicates healthy vegetation, while a very low value close to -1 indicates recently burned areas. Unburned areas are normally assigned values close to 0. Thresholding was applied to extract these areas recently burned, covering 5,000 hectares in the province of Sidi Bel Abbes.

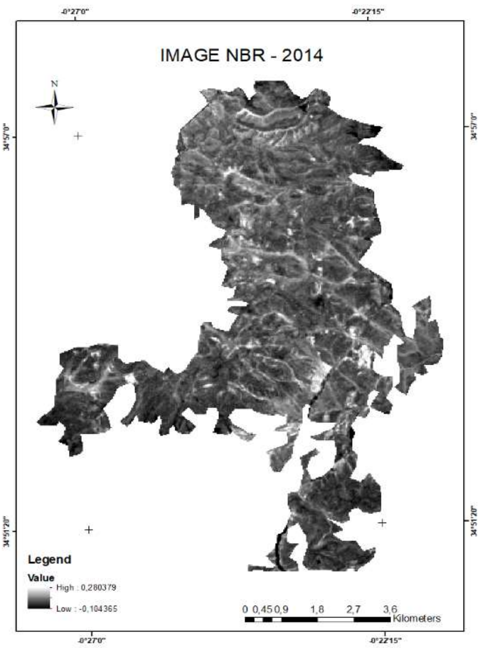

Figure 2. Image NBR - 2014

The developed post-fire stability index requires the calculation of NBR and NBR2, the latter using Landsat OLI8 satellite channels SWIR1 and SWIR2 as basic spectral indices. The result of NBR2 is in the the following figures:

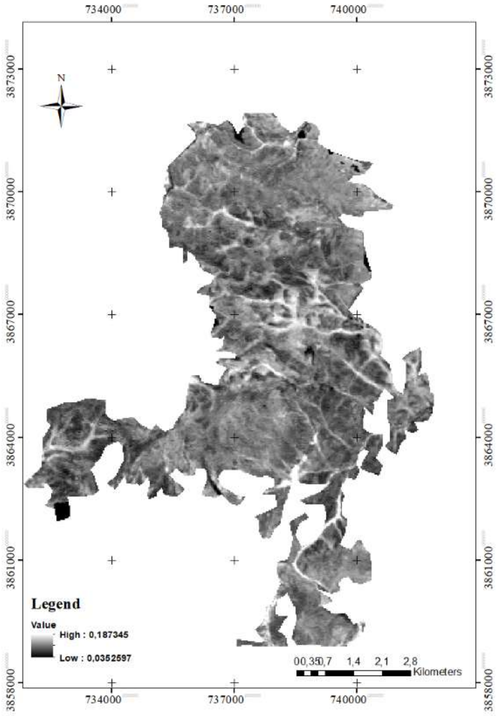

Figure 3. Image NBR2 - 2013

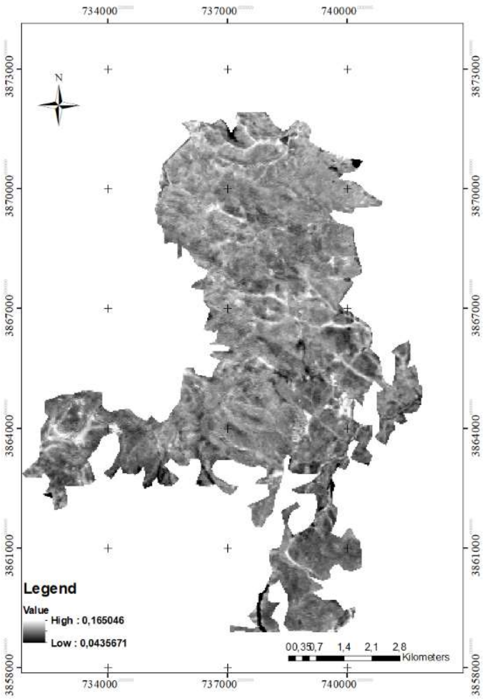

Figure 4. Image NBR2 - 2014

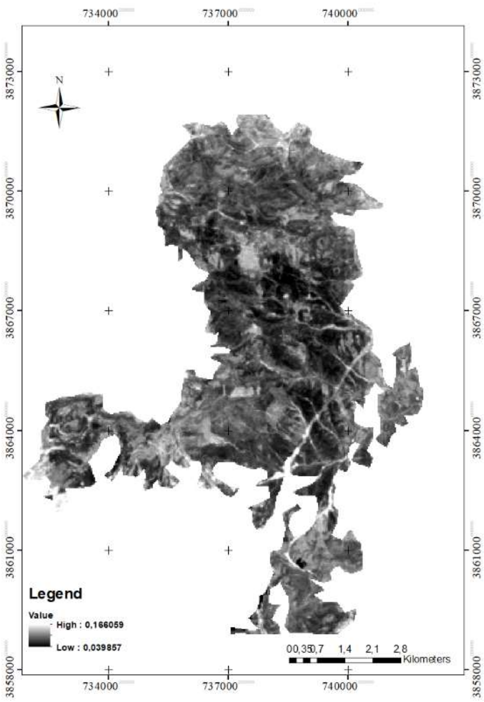

Figure 5. Image NBR2 - 2016

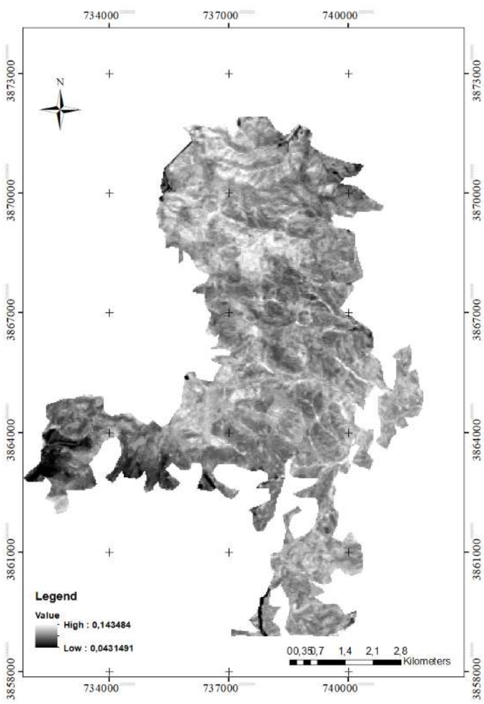

Figure 6. Image NBR2 - 2020

3.2.1 Classification result

We used the image obtained in 2013 before the fire to perform a supervised maximum likelihood classification in order to obtain the different classes of forest vegetation that make up the forest that suffered the fire in 2014. This information will inform us about the combustibility and the speed of fire propagation according to the species. Four main classes were obtained, see the following figure:

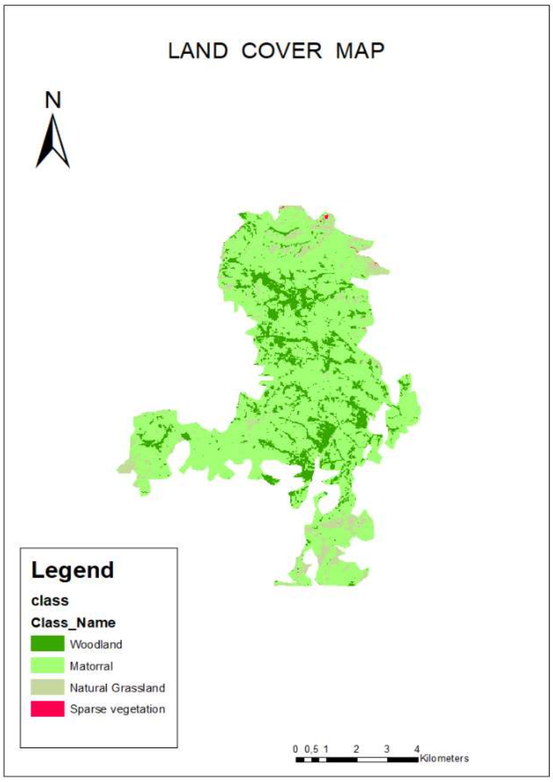

Figure 7. Image classification 2013

4. Results and Discussion

The literature review on Thuja (Boudy, 1950) shows that its post-fire regeneration depends on factors in the studied environment (climate, topography, pedology, state and characteristics of the pre-fire vegetation, etc.).
The djebel site in the commune of Merine is characterized by fairly uniform geology and pedology as well as the same climate. Therefore, to better assess post-fire regeneration and determine the contribution of the stability index, we proceed by:

4.1 Segmentation of NDVI

Segmenting NDVI images two years after fire (2016) and six years after fire (2020), allows us to limit the number of classes reflecting the regeneration dynamics and to interpret them more easily.
Furthermore, segmenting the NDVI images reflects the procedures followed to group pixels to form areas that can be interpreted as thematic classes. We obtained four classes based on vegetation density. This study uses the so-called pixel-by-pixel segmentation approach (Caloz and Collet, 2001). In this case, clustering is based solely on the criterion of spectral similarity between pixels. Two pixels are said to be similar if their respective spectral luminance values are similar, and in this case, spatial zoning is simply the result of classifying the pixels into categories, the results are in the following figures:

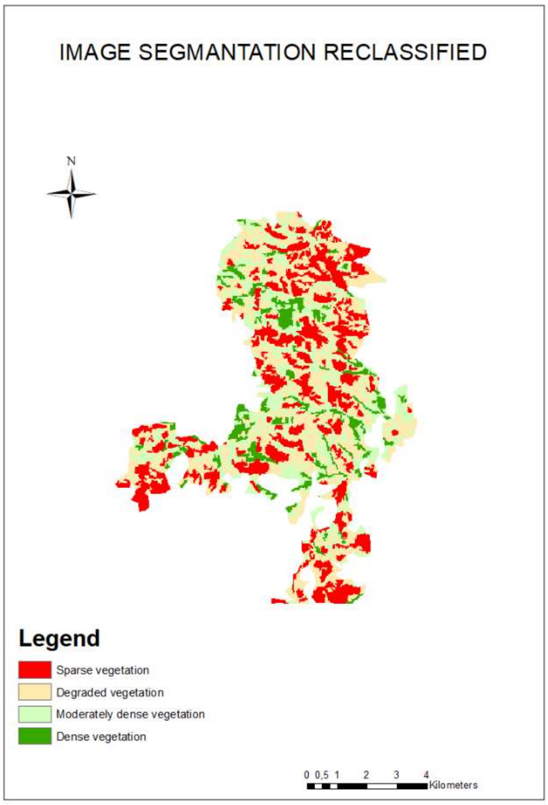

Figure 8. Image segmentation 2016

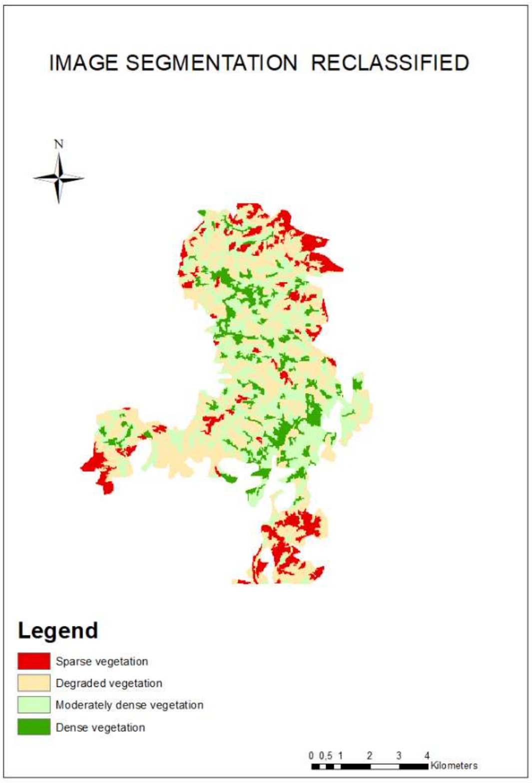

Figure 10. Image segmentation 2013

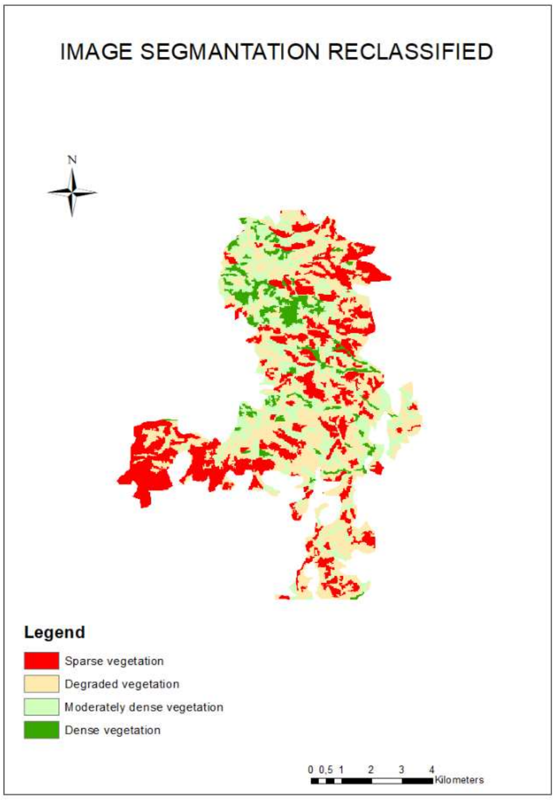

Figure 9. Image segmentation 2020

In the following table, we see the mutation and variation of vegetation density before and after fire.

Before and after fire 2014	2013 ha	2016 ha	2020 ha
Sparse vegetation	635,49	1452,51	1494,99
Degraded vegetation	2202,03	1946,61	2068,65
Moderately dense vegetation	1736,73	1293,21	1232,19
Dense vegetation	582,84	464,76	361,26

Table 2. vegetation density result by segmentation of NDVI

4.2 Change Detection: Normalized Difference Vegetation Index Differentiation (DNDVI)

The Normalized Difference Vegetation Index (NDVI), which is a ratio between near-infrared and red, is designed to measure the greenness and density of vegetation captured in a satellite image. The graphical representation of this index shows that healthy vegetation exhibits a very characteristic spectral reflectance curve. The NDVI is this difference expressed as a number, ranging from -1 to 1.

The NDVI of plant species in general, calculated regularly over several periods, can reveal a wealth of information, particularly on plant health, vegetation density, and its mutations.

In our case, to measure changes in biomass, we calculated the Differentiation NDVI (DNDVI). This method calculates NDVI values between images acquired on two different dates. It should be noted that before applying the NDVI differentiation, the NDVI image for each date was generated with a value range between -1 and +1. We then created a differential NDVI (DNDVI) image by subtracting the 2013 NDVI image from the 2016 NDVI image, as shown in the equation:

$$DNDVI = NDVI\ (2016) - NDVI\ (2013) \qquad (4)$$

And so on, from 2013 to 2020, to observe vegetation changes over a long period. To identify changed areas in an image from different dates, we used a thresholding technique based on the histogram of the differenced image. The results show that significant changes are located in the tails of the histogram distribution, while pixels showing no significant changes tend to cluster around the averages. These results were transformed into representative maps according to four degrees : no vegetation recovery, slow vegetation recovery, average vegetation recovery, and fast vegetation recovery.

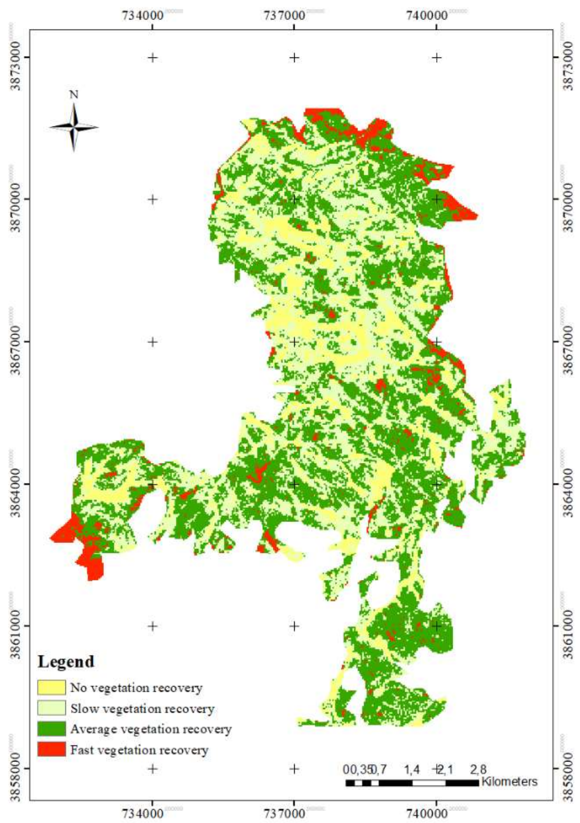

Figure 11. DNDVI: [NDVI2016 - NDVI2013]

At this stage, the analysis focuses primarily on classification changes from the initial pre-fire state. Alternatively, for each class in the initial state, the analysis identifies the classes where pixels are transferred in the final image state. This is because the changes are reported as areas.

Comparing these two figures (Figures 11 and 12) shows that the average vegetation recovery and the fast vegetation recovery per class have increased in area, indicating that post-fire forest regeneration becomes significant after a few years.

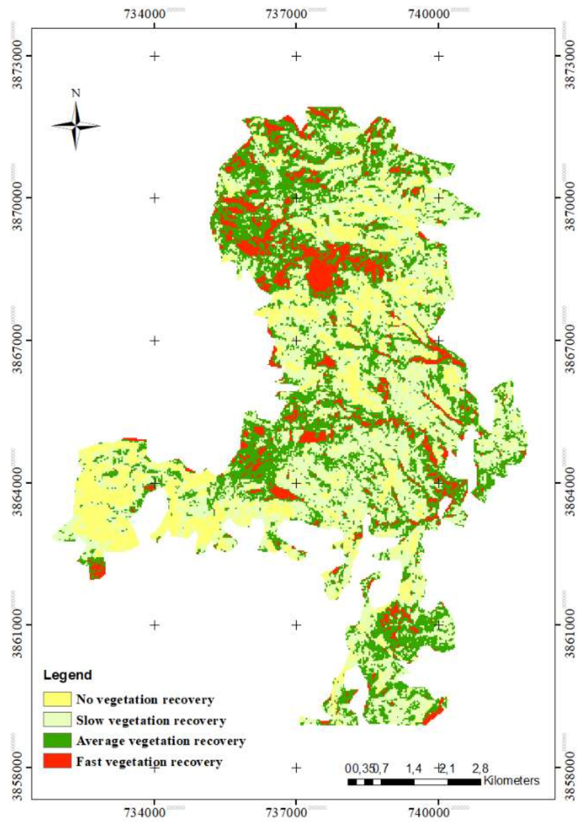

Figure 12. DNDVI: [NDVI2020 - NDVI2013]

4.3 The post-fire stability index (PFSI)

This new approach to post-fire monitoring and recovery using satellite imagery, which we present here, is based on the concept that a disturbed state of a system results in increasing or decreasing rates of change.
While undisturbed, unchanged, or recovered states are characterized by rates of change close to zero.

To further determine the performance and relevance of the post-fire stability index, we used alternative vegetation recovery approaches through time-series image analysis, NDVI, and image segmentation, followed by independent validation using post-fire vegetation surveys conducted one year after the fire in 2013. This post-fire stability index has proven to be a powerful model for field measurements of post-fire vegetative response. Higher values of the post-fire stability index indicate higher levels of post-fire regrowth.
This post-fire stability index therefore offers a practical solution for consistent, large-scale monitoring of post-fire regeneration using satellite imagery.

Therefore, we can state that the post-fire stability index examines the rate of change in the years following the fire, for all severity classes, including unburned areas. Typically, after a fire, increases in NBR2 occur over several years due to the rapid increase in vegetative biomass.
Post-fire stability index values close to zero at a given time step are not sufficient, on their own, to diagnose a stable

system state. Index values for all severity classes must also be synchronous with the surrounding unburned environment over several consecutive years. Interannual variations are expected in forest systems, even in the absence of fire-related changes, due to a variety of natural and anthropogenic processes occurring at various spatial and temporal scales (Kennedy et al., 2014). Using the Post-Fire Stability Index (PFSI) results, we can visually and statistically compare the spectral variations of burned areas with those of surrounding unburned areas on an annual basis. This allows for a better understanding of the spatial and temporal patterns of post-fire recovery across large landscapes. The figures below show the results of Post-Fire Stability Index calculated based on the years following the fire in our case (2014-2013, 2016-2014 and 2020-2014). A simple interpretation of these results clearly shows the areas where vegetation recovery is occurring at a fast rate.

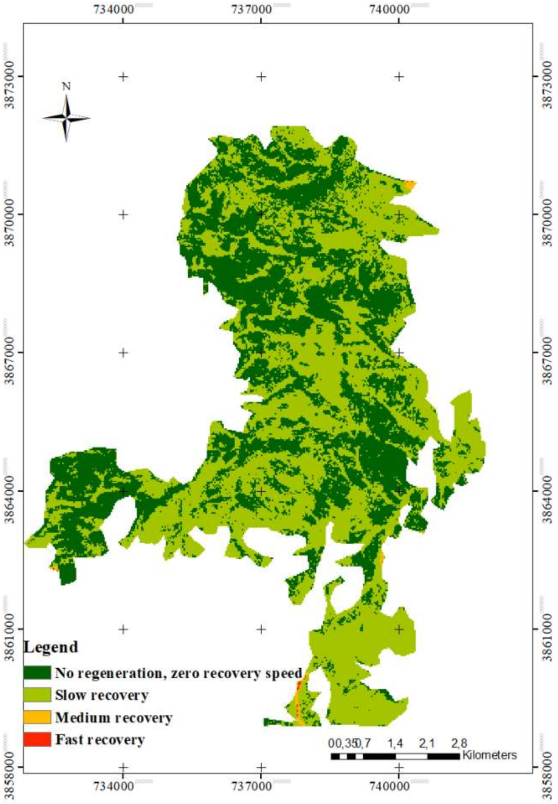

Figure 13. PFSI : Post-Fire Stability Index (2014-2013)

The PFSI index takes on higher values when there is strong recovery. The PFSI image for the Sidi Bel Abbès site was calculated using the pre-fire NBR2 image from 2013 (Figure 3) and the post-fire NBR2 image from 2014, 2016, and 2020 (Figures 4, 5, and 6).

The PFSI image obtained for the state of regeneration in 2014, a few months after the fire (Figure 13), shows that almost the entire burned area exhibits a very low index, represented by zero or low regeneration classes, indicating that the post-fire recovery rate is lower than the pre-fire recovery rate. The vegetation has not yet had the time necessary to reach a medium or high recovery rate.

For 2016 (Figure 14), we see moderate regeneration occurring in the burned area, where the area was covered with sparse vegetation, implying a less severe fire.

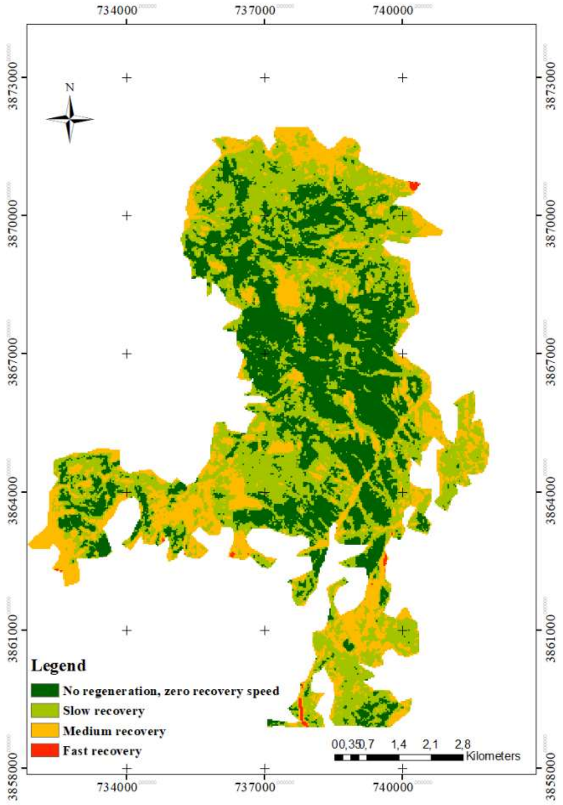

Figure 14. PFSI : Post-Fire Stability Index (2016-2014)

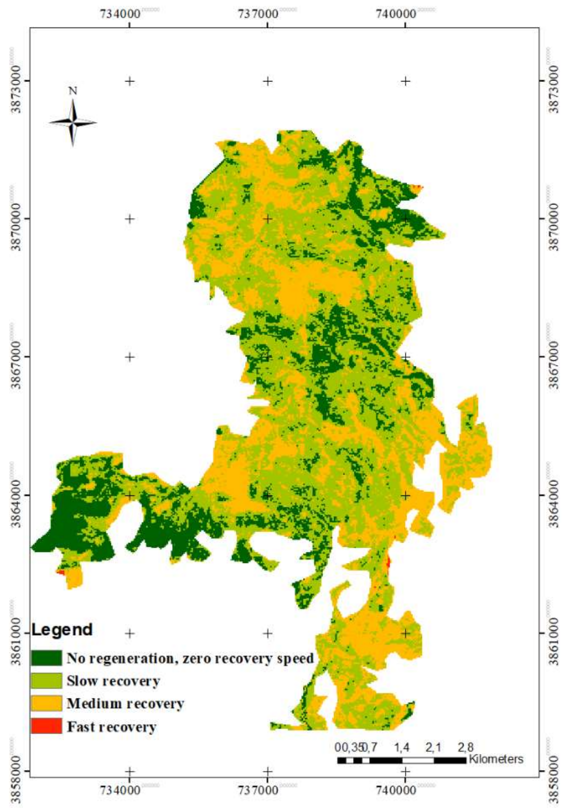

Figure 15. PFSI : Post-Fire Stability Index (2020-2014)

Comparing the results of PFSI with field data 2014, 2016 and 2020 we found that the forest species generally regenerate after three years and their rate of recovery become more important depending on topographic and climatic conditions.

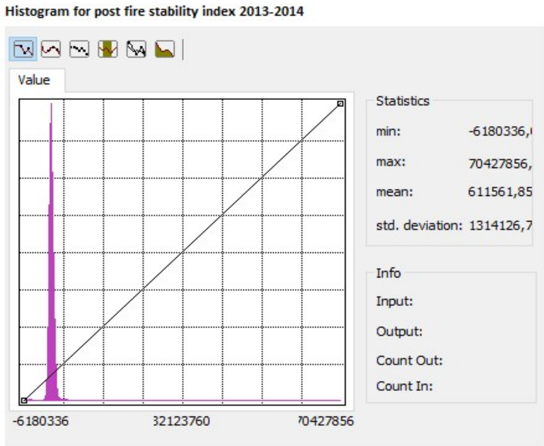

Figure 16 : histogramme PFSI 2014-2013

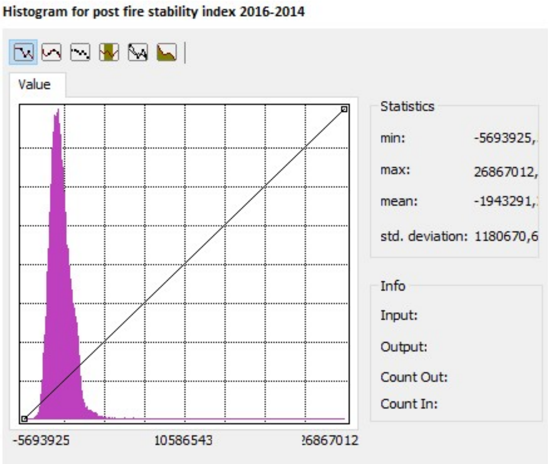

Figure 17: Histogramme PFSI 2016-2014

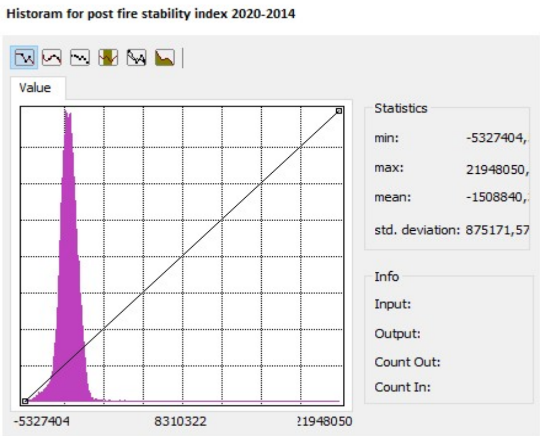

Figure 18: Histogramme PFSI 2020-2014

Reading the histograms, we see that positive post fire stability index (PFSI) values increase in importance with the number of years after the fire. This information confirms that post-fire regeneration becomes more significant from the second year after the fire, hence the natural cycle of forests.

5. Conclusion

Forest fires are a natural phenomenon and likely the main factor disrupting landscapes and triggering desertification processes in the semi-arid regions of the Mediterranean Basin. Therefore, to mitigate this situation, long-term measures are needed to prevent and restore fire-affected areas. The impact of forest fires is particularly acute in semi-arid and dry regions, where climate and dry fuels favor their spread. Therefore, sophisticated models capable of predicting the likely evolution of burned areas are essential.

This study demonstrated the potential of using remote sensing images and the stability index for monitoring and quantifying post-fire forest regeneration.

The post-fire stability index overcomes the main limitations of assessing post-fire regeneration relative to a previous reference situation. This index decouples post-fire regeneration from the pre-fire state, thus overcoming problems related to pre-fire spectral variability. In the forests of northeastern Algeria, forest fires generally occur during periods of drought. This was reflected in the annual fluctuation of NBR2 values in our time series data in 2016 and 2020, prior to the 2014 fire, across the entire study area.

However, the post-fire stability index provides a reliable method for consistently quantifying and monitoring post-fire regeneration over large areas and historical periods. It should be noted that remote sensing has inherent limitations in understanding this regeneration, as there is a relationship between reflectance values and the rate of post-fire forest regeneration.

However, combined field and remote sensing data show that post-fire regeneration is heterogeneous in the Sidi Bel Abbès region. It likely depends on topographic factors such as altitude, slope, and natural terrain exposure. These parameters will be the subject of a future study.

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