Manuscript title: Fire impact and topographic effect on post-fire natural regeneration of Aleppo pine forests of western Algeria.

Authors:

1. **RAFA Asma**

   Degree: Ph.D. Student in forestry

   Affiliation : Faculty of Natural and Life Sciences, Laboratory of Conservatory Management of Water, Soil, and Forests, University of Tlemcen, BP 119, 13000 Tlemcen, Algeria.

2. **BOUHRAOUA Rachid Tarik**

   Degree: Professor

   Affiliation : Faculty of Natural and Life Sciences, Laboratory of Conservatory Management of Water, Soil, and Forests, University of Tlemcen, BP 119, 13000 Tlemcen, Algeria.

3. **BERRICHI Faouzi**

   Degree: Forest engineer

   Affiliation: Algerian Space Agency (ASAL), BP 13, 31200 Arzew, Algeria.

4. **EL BOUHISSI Mayssara**

   Degree: Ph.D. In ecology

   Affiliation: Forestry Conservation of Sidi Bel Abbès, BP 222, 22000 Sidi Bel Abbès, Algeria.

5. **GHEFAR Mohamed**

   Degree: Ph.D. In forestry

   Affiliation: Inational Institute of Forestry Research, BP 37, 22000 Sidi Bel Abbès, Algeria.

6. **HADDOUCHE Driss**

   Degree: Professor

   Affiliation : Faculty of Natural and Life Sciences, Laboratory of Conservatory Management of Water, Soil, and Forests, University of Tlemcen, BP 119, 13000 Tlemcen, Algeria.

Corresponding author's : RAFA Asma

Abstract

The current study uses multitemporal satellite data and diverse information to analyse and evaluate the post-fire regeneration dynamics of Aleppo pine (*Pinus halepensis*) in the Guétarnia forest, a Mediterranean ecosystem in north-western Algeria, focusing on the interaction between fire impact, topographic features, and vegetation recovery. Utilizing remote sensing indices (Normalized Burn Ratio (NBR), Normalized Difference Vegetation Index (NDVI), and Normalized Recovery Index (NRI)) and field-based dendrometric measurements data collected from 25 m² sampling plot, the research examines seedling density, mortality rates, and growth patterns across varying fire severity classes and landscape characteristics. Results reveal that low-severity fires promote high seedling density (32,000 seedlings/ha) but increase competition induced mortality (17.79%), while high severity fires result in lower density (15,100 seedlings/ha) but more uniform growth due to reduced competition. Topographic factors, including slope and aspect, significantly influence regeneration outcome, with medium slopes (12–25%) supporting optimal recovery and south-facing slope exhibiting higher mortality rates (27.81%) due to water stress. The findings emphasize the need for adaptive post-fire management strategies, such as thinning in low severity zones and active restoration in high severity areas, to enhance forest resilience in the face of increasing wildfire threats.

Keywords: wildfire, topography, Aleppo pine, post-fire regeneration, indices.

Introduction

Forests ecosystems are an essential natural asset, providing an essential ecological balance and serving as an invaluable global resource (Ghorbanzadeh et al., 2019). They are particularly important for local economies, providing livelihoods and socio-cultural benefits for communities living near forested areas. Furthermore, forests significantly influence regional climatic patterns, emphasizing their ecological and environmental importance.

The world's forest area is estimated at 4.06 billion hectares (ha), representing approximately 31% of the total land area. This represents a significant decrease from the historical level, primarily because of multiple anthropogenic activities. Africa had the highest annual net forest loss rate in 2010-2020, with 3.9 million hectares (FAO, 2020). The analysis of documents related to the dynamic of forest cover in Algeria reveals those two centuries ago, it extended over more than 6 million hectares**.** Today, this area has been reduced to 4.2 million hectares, of which 2 million hectares consist of degraded formations (matorral, maquis, and garrigues). Natural forests now cover only 1.3 million hectares (Tatar, 2012).

Forest fires are significant natural disturbance that profoundly alter forest ecosystems by affecting their composition, structure, and ecological functions (Pausas & Keeley, 2009). In Algeria, between 1985 and 2010, forest fires devastated approximately 910,640 hectares, with an average of 35,025 hectares burned per year (Boukerker, 2016).

In Mediterranean regions, the Aleppo pine (*Pinus halepensis*) is a keystone species that demonstrates remarkable resilience to wildfires. This resilience is primarily because of its natural recovery mechanisms, particularly the dispersal of seeds from serotinous cones, which store them in the canopy and release them after a fire. This strategy enables rapid and massive post-fire vegetation renewal, ensuring the long-term persistence of fire-adapted tree stands (Pimont et al., 2014; Mauri & Pons, 2019). However, the intensity and the severity of fires, combined with the initial stand structure before the fire, the quality and quantity of the canopy seed bank, and topographic characteristics, play a critical role in determining the success of the regeneration process (Fernández-García et al. 2019). These factors influence not only immediate post-fire renewal but also the long-term recovery and sustainability of forest ecosystems.

Several studies have explored the dynamics of post-fire regeneration in pine forests, shedding light on the complex interplay between fire severity, topography, and ecological recovery. Research conducted across the Mediterranean basin, such as Fernández-García et al. (2019), Vennetier (2020), and Rodríguez-García et al. (2022), has provided valuable insights into the factors influencing forest recovery, particularly in fireprone ecosystems. In Algeria, efforts by Madoui et al. (2016) and Elhadj et al. (2021) have expanded our understanding of wildfire impacts, focusing on fire behavior and its effects on the forest ecosystem. Furthermore, broader wildfire-related research in the region, including studies by Ghefar & Bouazzaoui (2021), and El Bouhissi et al. (2024), have emphasised the significant ecological and socioeconomic consequences of wildfires. Although there has been increasing research on wildfire impacts in the region, studies specifically focused on the natural restoration of Aleppo pine (Pinus halepensis) in the post-fire context remain scarce. Our study provides the first analysis of Aleppo pine the post-fire regeneration dynamics in this region.

Topographic features, such as slope and aspect, significantly interact with fire dynamics to shape the post-fire regeneration environment. These interactions influence fire spread, intensity, and the creation of microsites conducive for seedling establishment. For instance, south-facing slopes, which are typically exposed to higher solar radiation, tend to be warmer and drier, resulting in slower recovery compared to the cooler, more humid north-

facing slopes (Rodrigo et al., 2004). Similarly, steep slopes are particularly prone to post-fire erosion, which can strip away essential soil nutrients and hinder seedling establishment (Shakesby & Doerr, 2006). These complex relationships underscore the importance of considering both fire severity and topographic variability when assessing the resilience and recovery potential of Mediterranean forests. Understanding these interactions is crucial for developing adaptive management strategies aimed at enhancing forest recovery and longterm ecological stability.

This research examines the interaction between fire severity and landscape features factors incorporating remote sensing indices for analyzing the post-fire regeneration process of Aleppo pine in the Sidi Bel Abbès region of northwestern Algeria. Aleppo pine formations are predominant in this region, covering 63,432 hectares, which represents 97% of the total forested area of the wilaya. The region experiences frequent wildfires, some of which are recurrent, with an annual average of 5,206 hectares burned, accounting for 2.53% of the total forested area (Rafa, 2017).

This study sheds light on the key factors influencing regeneration, mortality, and growth patterns. Additionally, it provides practical recommendations for post-fire management strategies, including targeted interventions in high severity zones and adaptive measures for enhancing forest resilience against future wildfire

Methods

1. Study area

The Guetarnia forest is situated between latitudes (35°14’15’’ N) and (35°20’14” N) and longitudes (0°09’44’’ W) and (0°20’17” W) (Figure 1). It is characterized by rugged landscape with altitudes ranging from 412 to 813 meters, predominantly featuring north and south-facing slopes. Slopes vary between 0° and 30%, with over 55% of the area having slopes between 15% and 30%. Flatter areas (0° to 15°) are also present, particularly on undulating plateaus that are favorable for forest vegetations development (Belgherbi, 2002). The forest lithology consists of Miocene and Cretaceous substrates, overlaid by quaternary formations such as calcareous crusts, sandy clays, and sands. The soils are shallow, ranging from 30 to 40 cm, and are primarily classified as redzina and calcareous brown soils (Dalloni, 1953; Belgherbi, 2002). Bioclimatically, the forest belongs to a semi-arid, temperate zone, with an average annual rainfall of 344 mm and an annual evaporation rate of 169 mm (Benbakkar et al., 2024). This region experiences two distinct seasons: a cold season from November to April, with minimum temperatures dropping below 3°C, and a hot season from May to October, with maximum temperatures reaching 35°C (Belgherbi et al., 2018). Winds

are frequent, with an average annual speed of 28 m/s, while the average annual humidity is 76% (Benbakkar et al., 2024). Spanning an area of 7321 hectares, the forest is dominated by *Pinus halepensis* (*Aleppo pine*), *Tetraclinis articulata*, and *Quercus rotundifolia*. The floristic composition include, in order of importance based on recovery rate, *Pistacia lentiscus*, *Phillyrea angustifolia*, *Quercus coccifera*, *Cistus villosus*, *Calicotum spinosa*, and *Stipa tenacissima*. Because of its vegetation composition and climatic conditions, the Guetarnia forest is classified as a high fire risk area.

In 2016, a severe wildfire devastated 895 hectares, including 208 hectares of *Pinus halepensis* stands and 686.71 hectares of shrub vegetation, underscoring the region's vulnerability to wildfire.

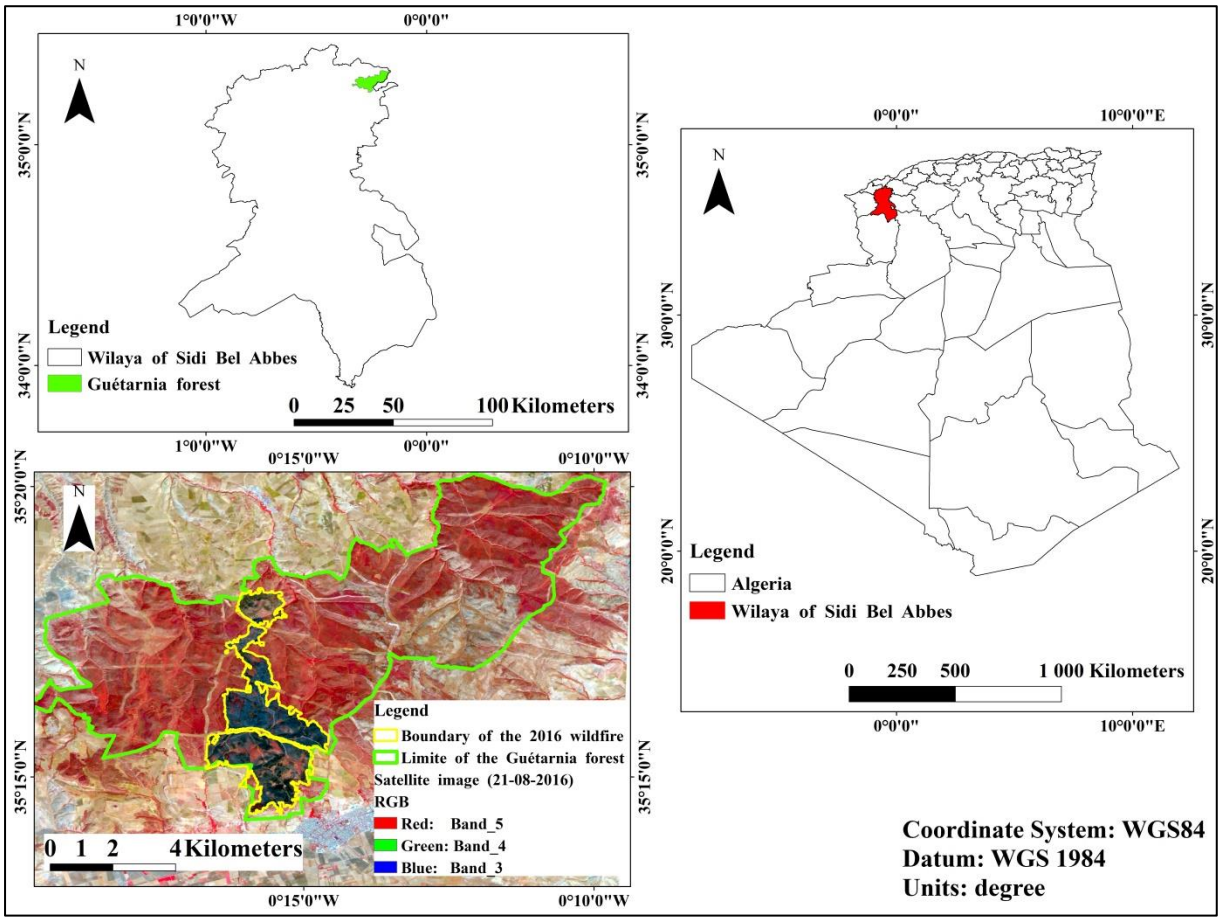


Figure 1. Geographical location of the study area.

2. Acquisition of geospatial data

Wildfires significantly impact vegetation and ecosystems, and necessitate detailed analyses for understanding their effects and recovery dynamics. To this end, we have used satellite imagery and indices in this study for evaluating the effect of topography and fire impact on post-fire vegetation recovery. The methodological approach is illustrated in the graph in Figure 2.

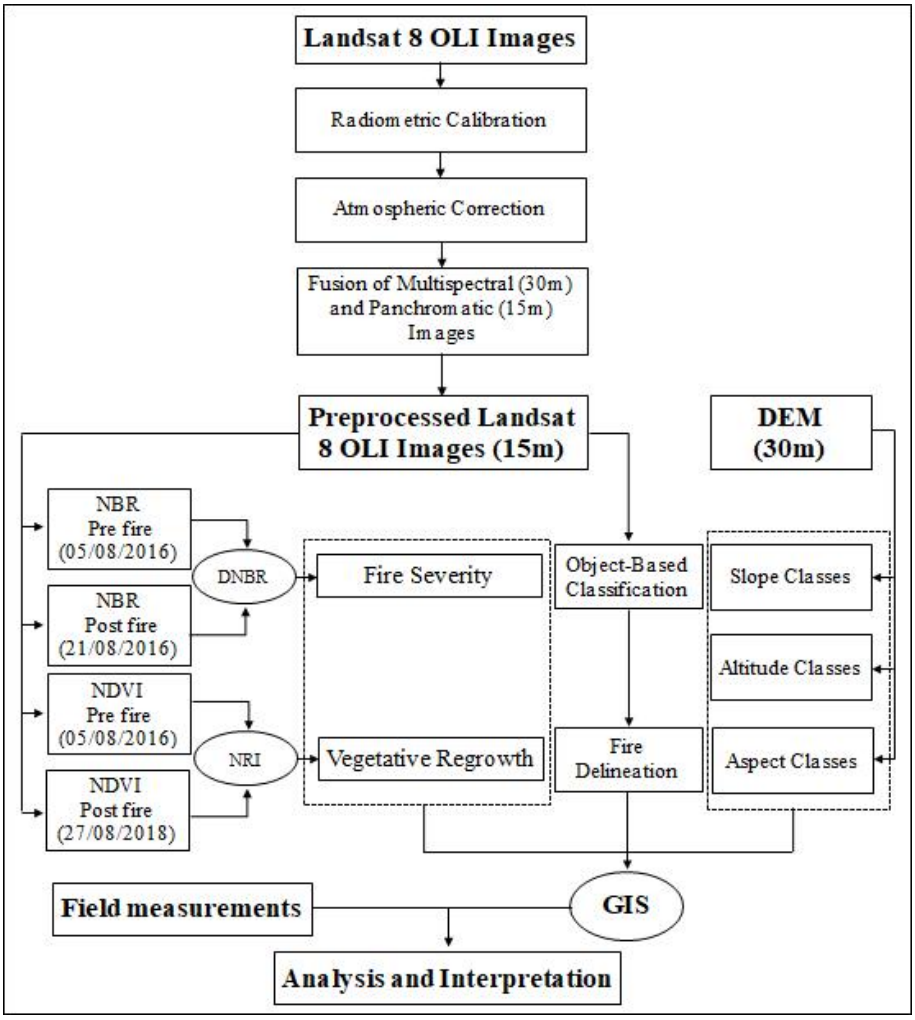


Figure 2. Graph of establishment process of GIS.

This study used three Landsat 8 OLI/TIRS satellite images (Fusion multispectral: 30m and panchromatic: 15m), acquired between 2016 and 2018 through the USGS Earth Explorer platform. These images were selected to represent critical timeframes: before the fire (August 5, 2016), immediately after the fire (August 21, 2016), and two years post-fire (August 27, 2018). The images, captured during the summer and with less than 30% cloud cover, were chosen for optimizing vegetation index analysis and minimize interference from seasonal vegetation changes and cloud cover, following guidelines for seasonal vegetation dynamics analysis (Zhu & Woodcock, 2012).

To improve image quality and segmentation accuracy, pre-processing steps included radiometric calibration (Chander et al., 2009), atmospheric correction (Gao et al., 2009), and image fusion for improving spatial resolution. A Digital Elevation Model (DEM), 30 m spatial resolution, was used to extract detailed landscap parameters, including altitude, slope, and aspect. Slopes were categorized as low (0–12%), moderate (12–25%), and steep (>25%), while elevation was grouped into 100-meter intervals. Aspects were classified into four

primary orientations: North, East, South, and West. These classifications adhere to established standards for examining landscape features and post-fire vegetation dynamics (Pausas & Keeley, 2014).

The analysis incorporated three vegetation indices Normalized Burn Ratio (NBR), Normalized Difference Vegetation Index (NDVI), and Normalized Recovery Index (NRI) calculated both pre and post-fire for assessing fire impact and vegetation recovery. The Normalized Burn Ratio (NBR) used near infrared (NIR) and shortwave infrared (SWIR) spectral bands to detect burned areas and evaluate burn severity. The difference between pre and post-fire NBR values provided five burn severity categories: unburned, low severity, low to moderate severity, moderate to high severity, and high severity (Key & Benson, 2006). The Normalized Difference Vegetation Index (NDVI), derived from red (R) and near-infrared (NIR) spectral bands, measured vegetation health, with values ranging from -1 to +1, reflecting vegetation density and vigor (Cherki & Gmira, 2013). The Normalized Recovery Index (NRI), based on bi-temporal NDVI changes, quantified vegetation recovery post-fire, ranging from 0 (no recovery) to 1 (maximum recovery) (Chen et al., 2011; Haddouche et al., 2011).

3. Data plots

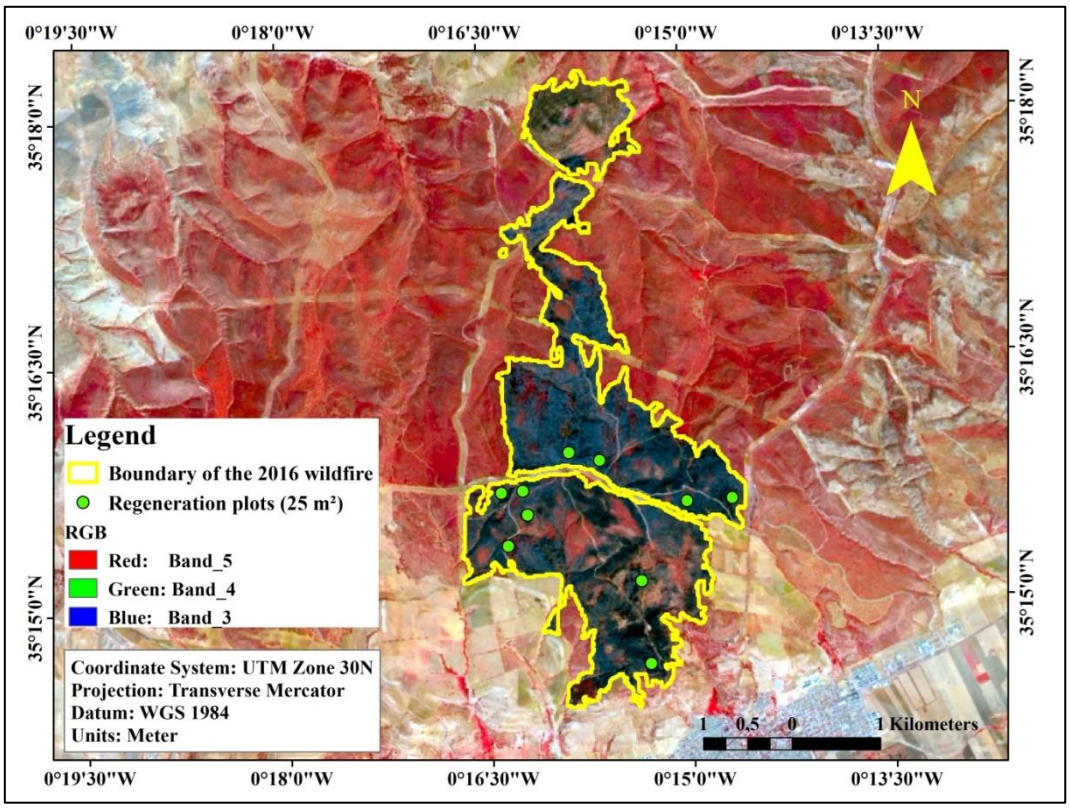


Figure 3. Boundary of the 2016 wildfire and regeneration plots in the Guétarnia forest (Satellite image from August 21, 2016).

To complete the data analysis using Geographic Information Systems and remote sensing, as well as to conduct a detailed assessment of post-fire regeneration, we established 10 square plots of 25 m² in October 2024 (eight years after the fire) (Figure 3). These plots are distributed to ensure representation across all fire severity classes identified through the Differenced Normalized Burn Ratio (dNBR). This approach is aligned with an established methodology for studying fire-affected ecosystems (Morgan et al., 2014).

Several parameters were measured: i) Dendrometric parameters: Diameter measurements at the collar were taken using a caliper for millimetre level precision, while seedling height was recorded from the collar to the apex using a measuring tape. ii) Density: The number of seedlings was counted within each plot and then extrapolated per hectare (seedlings.ha^{-1}). iii) Health status: This involved classifying seedlings as either alive or dead to determine the mortality rate.

The dominant diameter and height were determined by averaging the tallest seedlings in each plot.The count of dead seedlings allowed calculation of the mortality rate, a critical metric for assessing post-fire resilience (Keeley, 1986). Dead seedlings were excluded from growth analyses, following standard practices in regeneration studies. This dual-phase methodology integrating remote sensing with field-based dendrometric data analysis offers a robust framework for evaluating and analysing the dynamics of ecosystem Restoration.

Results

By integrating remote sensing indices, field-based dendrometric measurements data, and terrain characteristics, we analyzed key regeneration variables, including seedling density, mortality rates, and growth patterns across different levels of fire severity.

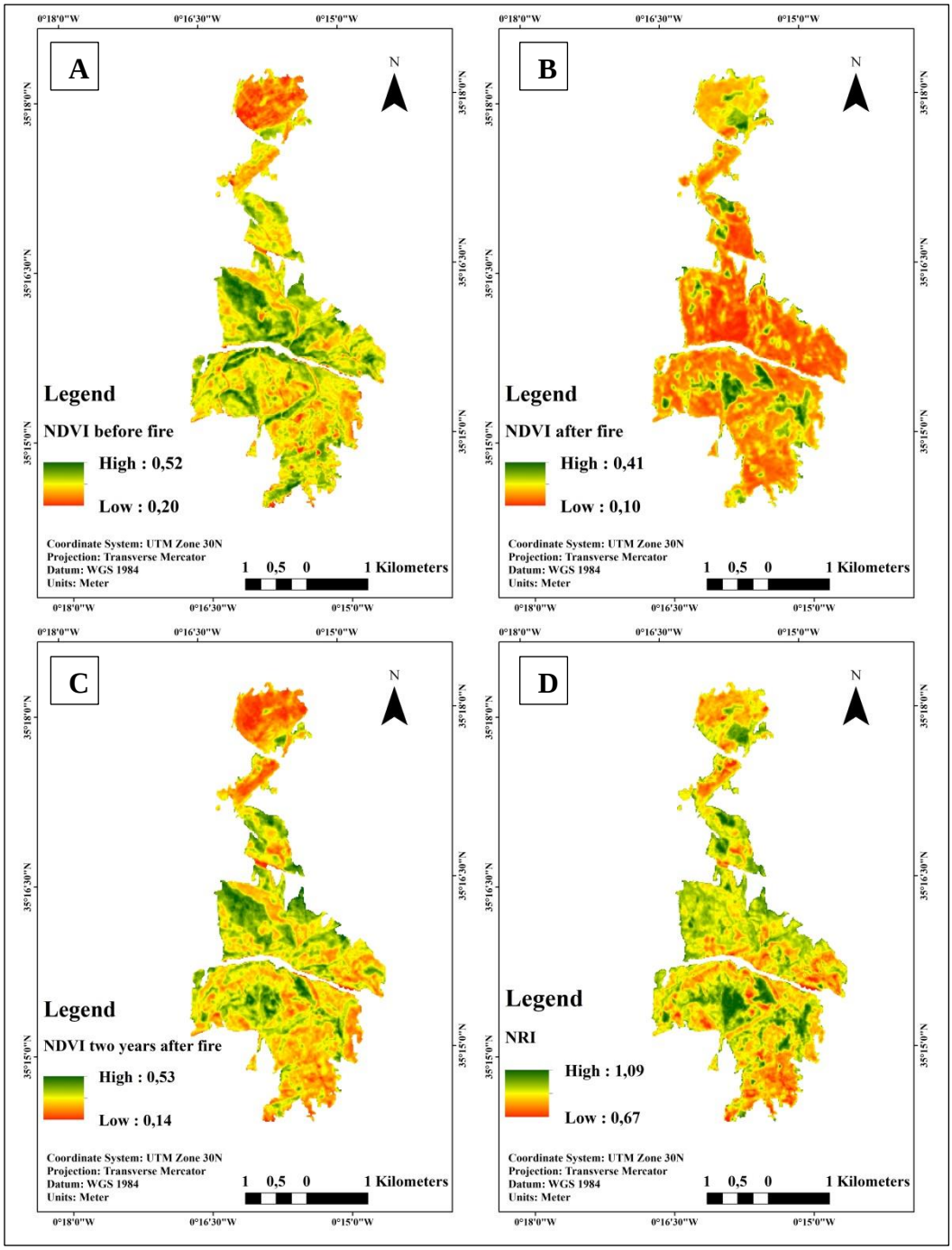


Figure 4. A. NDVI before fire (05/08/2016), **B.** NDVI after fire (21/08/2016), **C.** NDVI two years after fire (27/08/2018)**, D.** NRI (27/08/2018).

The Normalized Difference Vegetation Index (NDVI) and the Normalized Regeneration Index (NRI) maps in Figure 4, clearly illustrate the impact of the fire on vegetation and its recovery. Before the fire, areas with high NDVI values (0.20 to 0.52) indicated dense and well-developed vegetation. Immediately after the fire, a significant decrease in NDVI was observed (ranging from 0.10 to 0.41), especially in the most affected areas, indicating a substantial loss of plant biomass. However, two years later, a progressive recovery in NDVI values (0.14 to 0.53) signaling active vegetation regeneration. Two years

after the fire, the post-fire recovery was also reflected in the NRI, with values ranged from 0.67 to 1.09. Values between 0.67 and 1.09 indicate a high rate of vegetations recovery, while values above 1 correspond to areas unaffected by the fire.

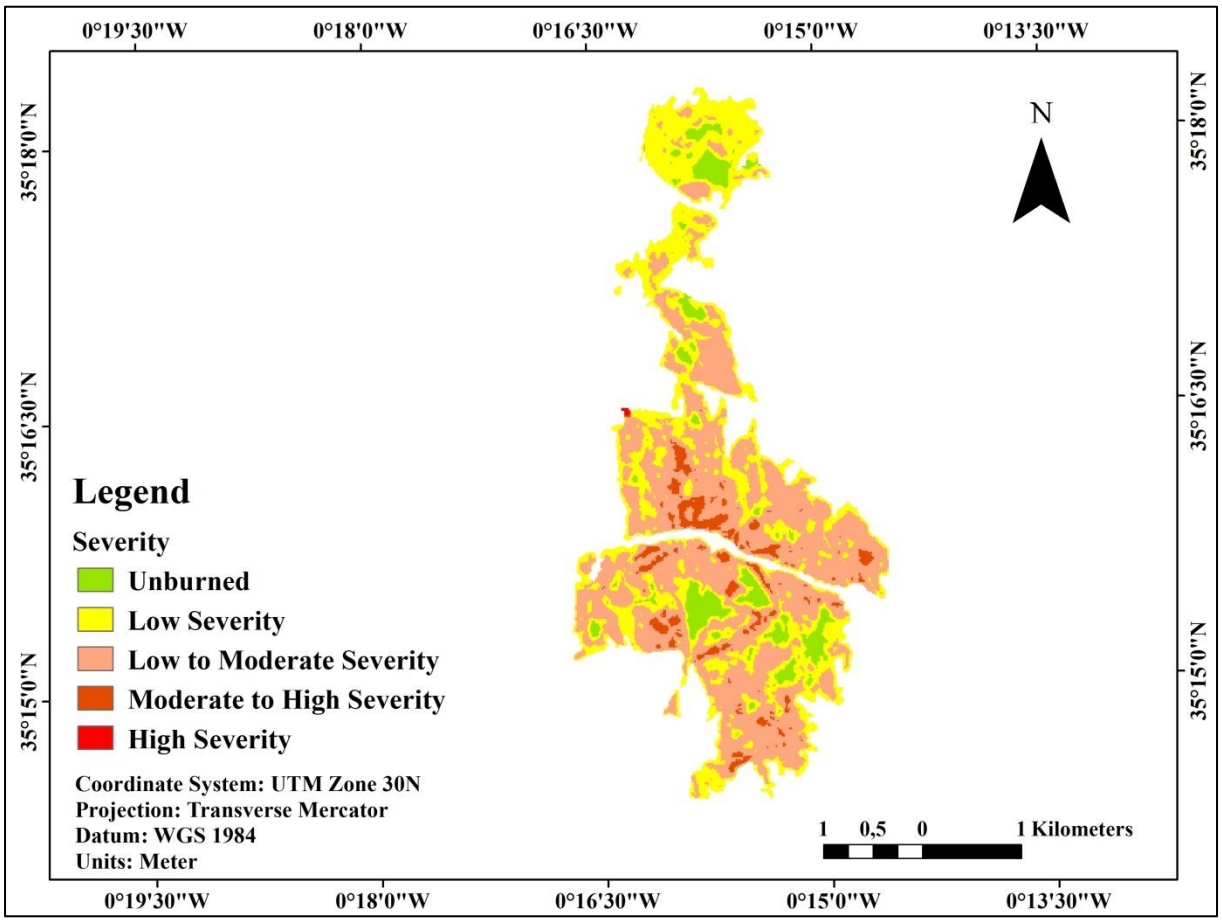


Figure 5. Map of fire severity classes in the Guétarnia forest wildfire (2016).

Based on the differentiation of the Normalized Burn Ratio (NBR), the fire impact reveals a pronounced spatial variability in the wildfire impact on the study area, with a marked dominance of low and low to moderate severity classes (Figure 5). Low to moderate severity zones, covering the largest area (466.58 hectares), are concentrated in the central region, suggesting a moderate-intensity fire that affected vegetation without causing complete destruction. Unburned zones, predominantly in the northern part (82.96 hectares), are composed of intact or minimally affected shrub formations, which may play a critical role in maintaining local ecosystem resilience. Low severity areas (303.10 hectares) indicate light fire activity across substantial portions of the site. In contrast, moderate to high severity regions (41.72 hectares) and high severity zones (0.45 hectares) are more restricted to the southern region, where vegetation suffers more significant damage (Table 1).

Table 1. Distribution of burned area by fire severity classes.

Severity	Area (Ha)	(%)
Unburned	82,96	9,27
Low Severity	303,10	33,87
Low to Moderate Severity	466,58	52,14
Moderate to High Severity	41,72	4,66
High Severity	0,45	0,05

Table 2 demonstrates the variation in seedling density, mortality rate, and growth (in terms of diameter and height) across differents fire severity classes. The results illustrates the contrasting effects of fire impact on regeneration, inter individual competition and environmental conditions.

Table 2. Variation in seedling density, mortality rate and growth in terms of diameter and height across fire severity classes.

Severity / Parameters		Low Severity	Low to Moderate Severity	Moderate to High Severity
Seedling Density/Ha		32000	34700	15100
Mortality rate (%)		17,79	18,44	12,1
Height (cm)	**Average height**	78,25	68,64	71,74
	Dominant height	111,25	123,47	95,54
	Maximum height	126	150,25	105,5
	Minimum height	32	23,5	36,25
Diameter (cm)	**Average diameter**	1,13	1,06	1,14
	Dominant diameter	1,63	1,56	1,51
	Maximum diameter	2	1,88	2,33
	Minimum diameter	0,4	0,4	0,45

In low-severity zones, regeneration density is high (32,000 seedlings/ha), with an average diameter of 1.13 cm, a dominant diameter of 1.63 cm, and a maximum diameter of 2 cm. The average height is 78.25 cm, with a dominant height of 111.25 cm and a maximum height of 126 cm. These areas indicate relatively preserved environment that supports rapid restoration. However, the high density leads to intense competition for resources, resulting in a mortality rate of 17.79%.

In low to moderate severity zones, seed density is increased to 34,700 seedlings/ha, reflecting favorable conditions for seed germination. Moderate intensity fires partially

damage vegetation, exposing soil and increasing light availability, which promotes germination. Despite these favorable conditions, the high density causes overcrowding, increasing mortality risk because of intraspecific competition, with a mortality rate of 18.44%. The average height in these zones is 68.64 cm, with a dominant height of 123.47 cm and a maximum height of 150.25 cm. The average diameter is 1.06 cm, with a dominant diameter of 1.56 cm and a maximum diameter of 1.88 cm.

In moderate to high severity zones, regeneration density drops significantly to 15,100 seedlings/ha, indicating the destructive impact of high intensity fires. These fires burn vegetation, seeds, and litter, severely limiting the initial restoration capacity. However, the lower density reduces competition for resources, allowing some seedlings to grow vigorously. This results in the lowest mortality rate (12.10%) among all severity classes. The average diameter is little higher (1.14 cm), while the dominant diameter is lower (1.51 cm). The maximum diameter reaches 2.33 cm, the highest among all classes, reflecting heterogeneous growth because of different environmental conditions. The average height is 71.74 cm, but the dominant height (95.54 cm) and maximum height (105.50 cm) are lower, reflecting slower overall growth.

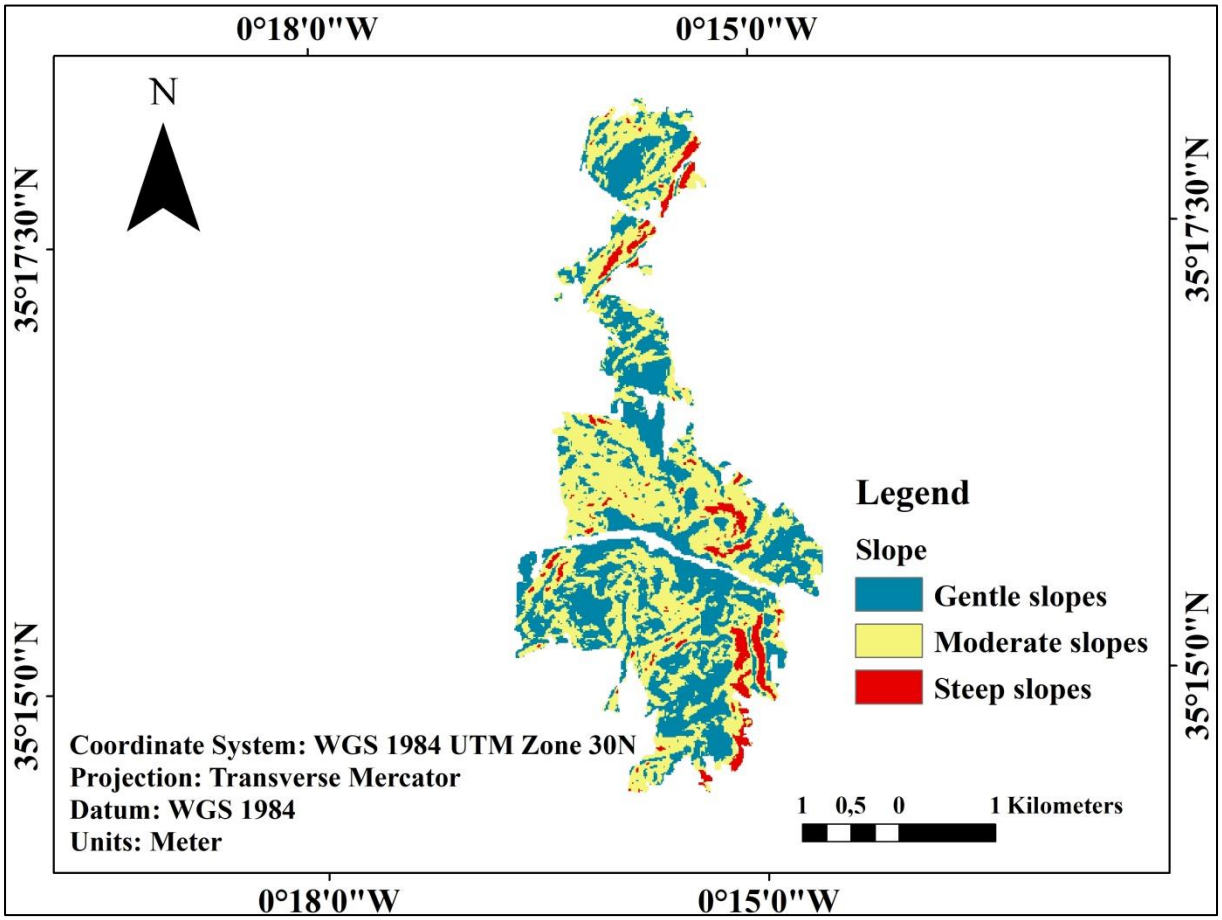


Figure 6. Map of slope classes in the Guétarnia forest wildfire (2016).

The analysis of burned areas across slope classes (Figure 6, Table 3) reveals that moderate slopes account for the largest affected area (455.10 ha), followed by low slopes (388.43 ha), and steep slopes (51.28 ha). The interaction between slope and severity indicates that medium slopes, with their diverse topography and dense vegetation, facilitate fire spread, particularly at low to moderate severity levels, affecting 239.55 ha. Additionally, gentle slopes, with fewer obstacles and nearly equal cover, have more uniform and rapid fire spread, burning 157.71 ha with low severity, 207.75 ha with low to moderate severity, and 20.61 with moderate to high severity. Steep slopes covering a much smaller area demonstrate limited fire spread, distributed across different severity classes (Table 3).

Table 3. Distribution and rate of burned area based on the resulting classes from the overlay of slope and fire severity

Slope	Area (Ha)	(%)	Severity	Area (Ha)	(%)
Gentle slopes	388,43	43,41	Unburned	40,05	4,48
			Low Severity	120,36	13,45
			Low to Moderate Severity	207,75	23,22
			Moderate to High Severity	20,26	2,26
Moderate slopes	455,10	50,86	Unburned	36,79	4,11
			Low Severity	157,71	17,63
			Low to Moderate Severity	239,55	26,77
			Moderate to High Severity	20,61	2,30
			High Severity	0,45	0,05
Steep slopes	51,28	05,72	Unburned	6,12	0,68
			Low Severity	25,02	2,80
			Low to Moderate Severity	19,28	2,15
			Moderate to High Severity	0,85	0,09

The influence of slope on seedling density, mortality, and growth reveals significant variations in post-fire regeneration conditions (Table 4). The table 4 indicates that moderate slopes support the highest density (29,500 seedlings/ha), followed by gentle slopes (27,200 seedlings/ha) and steep slopes (9,200 seedlings/ha), suggesting that moderate slopes provide an ideal balance of moisture and light for germination and survival. Mortality rates are highest on steep slopes (26.09%) because of the increased erosion and shallow soils, compared to gentle slopes (17.19%) and moderate slopes (11.42%). Growing patterns further highlight these differences, with seedlings on steep slopes exhibiting the largest maximum

(2.50 cm) and dominant diameter (1.88 cm) due to reduced competition from lower density. Moderate slopes show uniform growth, with stable soil conditions promoting moisture retention and nutrient disposal. Gentle slopes favour the best vegetative growth, attaining an average height of 78.63 cm and a maximum height of 114.4 cm. On moderate slopes, regeneration is more heterogeneous, with an average height of 60.50 cm and a maximum of 141.25 cm, while steep slopes show an average height of 82.88 cm and a maximum of 138 cm.

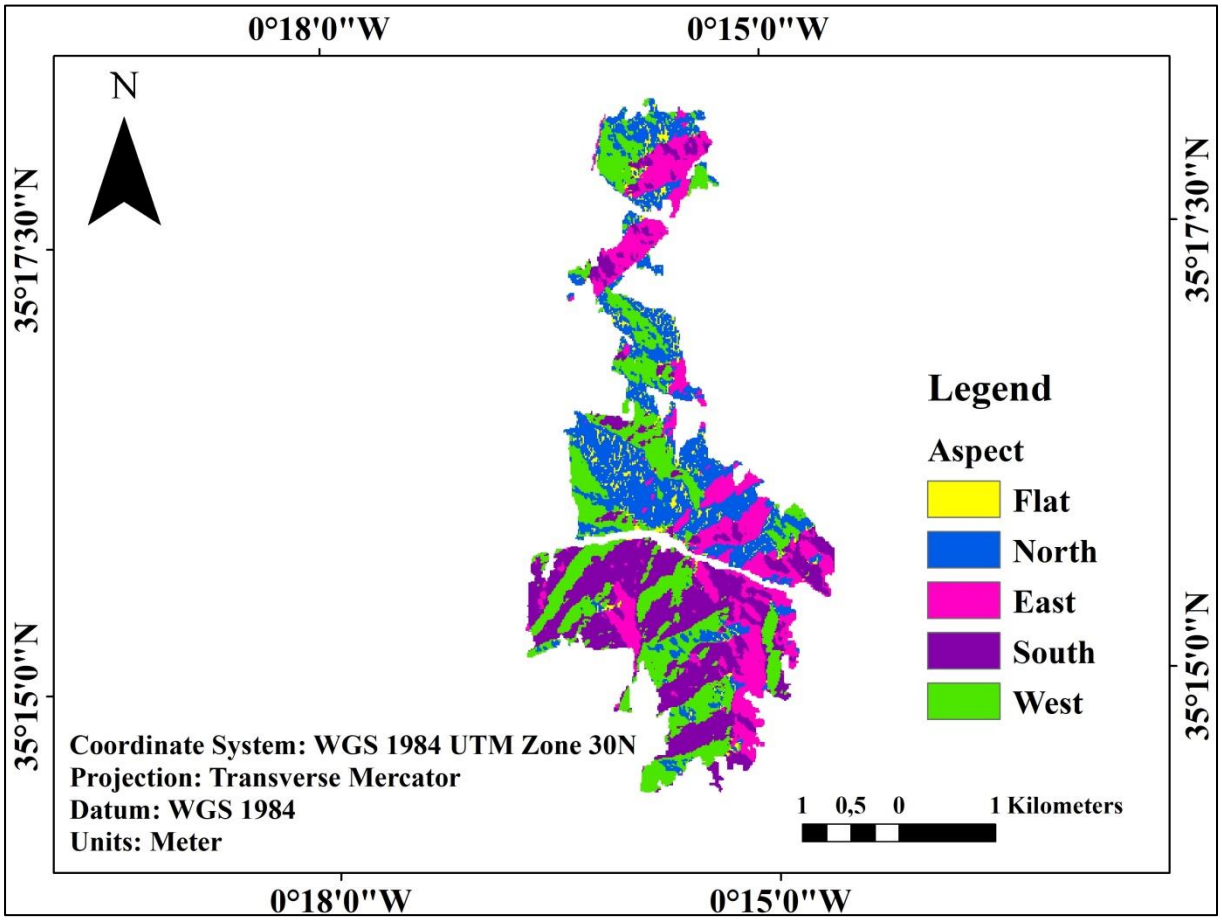


Figure 7. Map of aspect classes in the Guétarnia forest wildfire (2016).

The analysis of burned areas based on aspect shows distinct patterns in fire impact distribution (Figure 7, Table 5). South-facing slopes exhibit the largest affected area (239.74 ha), followed by west facing slopes (233.04 ha). As presented in Figure 7 and Table 5, most burned areas in these orientations fall into low to moderate severity classes (south: 62.48 ha in low severity and 141.65 ha in low to moderate severity; west: 93.28 ha in low severity and 108.71 ha in low to moderate severity). North-facing slopes account for 217.65 ha affected, with 119.93 ha classified as low to moderate severity. East facing slopes represent 176.37 ha of burned area, while flat areas show minimal impact with only 28.01 ha affected.

Table 5. Distribution and proportion of burned area based on the resulting classes from the overlay of aspect and fire severity

Aspect	Area (Ha)	(%)	Severity	Area (Ha)	(%)
East	176,37	19,71	Unburned	21,78	2,43
			Low Severity	66,33	7,41
			Low to Moderate Severity	82,55	9,23
			Moderate to High Severity	5,70	0,64
Flat	28,01	03,13	Unburned	2,90	0,32
			Low Severity	9,14	1,02
			Low to Moderate Severity	13,74	1,54
			Moderate to High Severity	2,20	0,25
			High Severity	0,03	0,00
North	217,65	24,32	Unburned	9,82	1,10
			Low Severity	71,86	8,03
			Low to Moderate Severity	119,93	13,40
			Moderate to High Severity	15,62	1,75
			High Severity	0,42	0,05
South	239,74	26,79	Unburned	26,23	2,93
			Low Severity	62,48	6,98
			Low to Moderate Severity	141,65	15,83
			Moderate to High Severity	9,37	1,05
West	233,04	26,04	Unburned	22,22	2,48
			Low Severity	93,28	10,42
			Low to Moderate Severity	108,71	12,15
			Moderate to High Severity	8,83	0,99

The post-fire regeneration of Aleppo pine shows significant variations based on slope aspects, with each orientation influencing seedling, mortality, and growth differently (Table 6). South-facing slopes support the highest regeneration (38,933 seedlings/ha), benefiting from abundant sunlight that promotes germination and establishment. However, these slopes also experience the highest mortality rate (27.81%) because of increased water stress and evapotranspiration. Despite this, seedlings on south-facing slopes show superior growth, with an average diameter of 1.25 cm and height of 77.82 cm, reflecting optimal photosynthesis conditions.

Table 6. Variation in seedling density, mortality rate and growth in terms of diameter and height according to aspect classes.

Aspect / Parameters		East	North	West	South
Seedling Density/Ha		11000	27000	23467	38933
Mortality rate (%)		28,67	1,11	4,92	27,81
Height (cm)	**Average height**	74,26	62,52	70,33	77,82
	Dominant height	118,58	88,6	100,13	127,92
	Maximum height	159	100,5	112	140
	Minimum height	40,5	28,5	29	26
Diameter (cm)	**Average diameter**	0,95	1,02	1,12	1,25
	Dominant diameter	1,52	1,46	1,47	1,72
	Maximum diameter	2	2,25	1,93	2,17
	Minimum diameter	0,4	0,4	0,43	0,43

In contrast, north-facing slopes demonstrate a lower density (27,000 seedlings/ha) but the lowest mortality rate (1.11%), attributed to higher moisture retention and reduced solar exposure. Growth on these slopes is slower, with an average diameter of 1.02 cm and height of 62.52 cm, probably because of limited light and thermal conditions. East-facing slopes exhibit the lowest density (11,000 seedlings/ha) and a high mortality rate (28.67%), with growth limited by challenging conditions such as reduced morning sunlight and increased drought. The average diameter and height on these slopes are 0.95 cm and 74.26 cm, respectively.

West-facing slopes display intermediate values in seedling (23,467 seedlings/ha) and mortality, balancing light availability and water constraints. Growth parameters, including an average diameter of 1.12 cm and height of 70.33 cm, reflect these moderate conditions. Collectively, these findings underscore the role of slope aspect in shaping recovery dynamics through its influence on microclimatic and environmental conditions.

Discussion

The findings of this study show the complex interactions between fire severity, landscape, and post-fire restoration dynamics, particularly in terms of regeneration, growth, and mortality in the Guétarnia forest. Seedlings were highest in low-severity fire zones, reaching 32,000 seedlings/ha, but this high density also led to intense competition for resources such as water, light, and nutrients, resulting in a mortality rate of 17.79% (Pausas & Vallejo, 1999). This aligns with previous studies showing that low-severity fires, while

promoting rapid regeneration, often create overcrowded conditions that increase seedling vulnerability to stress and mortality (Baeza et al., 2006). In contrast, high-severity fire zones revealed lower density (15,100 seedlings/ha) but more homogeneous growth, with seedlings showing larger diameters and heights. The reduced competition in these areas allowed surviving seedlings to grow more vigorously, as noted by Pausas & Keeley (2009), who emphasized that high intensity fire can act as a selective force, favoring the survival of the most resilient individuals.

Slope and exposure played an important role in seedling dynamics. Medium slopes (12–25%) accounted for the largest burned area, with low to moderate severity fires predominating, probably because of their moderate incline and dense vegetation, which facilitates fire spread (Alexandrian et al., 1999). Seedlings on these slopes showed intermediary growth patterns, with an average diameter of 1.63 cm and a maximum height of 141.25 cm, reflecting a balance between resource availability and competition. In contrast, steep slopes (>25%) acted as natural firebreaks, limiting fire spread. Seedlings on steep slopes exhibited the largest maximum diameter (2.50 cm) but also the highest mortality rate (26.09%), likely due to erosion and shallow soils (Certini, 2005). Aspect also influenced seedling dynamics, with south-facing slopes experiencing the highest density (38,933 seedlings/ha) but also the highest mortality rate (27.81%) because of water stress and excessive evapotranspiration (Rodríguez García et al., 2022). North-facing slopes, with higher moisture retention, showed lower mortality rates (1.11%) but slower growth, reflecting less favorable light and thermal conditions (Bale et al., 2002 ; Haddouche et al., 2011).

The analysis of NDVI and NRI provided valuable insights into vegetation recovery and its relationship with seedling dynamics. The sharp decline in NDVI immediately after the fire reflected significant biomass loss, consistent with findings by Viedma et al., (2015). However, the progressive recovery of NDVI two years post-fire indicated active vegetation regeneration, particularly in low to moderate severity zones, where seedling density was highest.

The implications of these findings for forest management are significant. Low severity zones, with their high regeneration, may require thinning interventions to reduce competition and improve long term resilience. In contrast, high severity zones may need active restoration efforts, such as reseeding and soil stabilization, to support regeneration (Baeza et al., 2006). The integration of remote sensing and GIS technologies, as demonstrated in this study, provides valuable tools for monitoring post-fire regeneration. Recent advancements in machine learning algorithms offer new opportunities for improving the accuracy of

burnseverity mapping and regeneration dynamics (Lentile et al., 2006). Additionally, using models for predicting future fire behavior can make adaptive strategies in the face of climate change (Moritz et al., 2014).

Conclusion

This study provides valuable insights into fire severity, landscape factors, and post-fire regeneration dynamics of Aleppo pine in the Guétarnia forest, northwestern Algeria. Integrating remote sensing indices (dNBR, NDVI, NRI) with detailed field measurements it underscores the critical role of fire in shaping seedling density, mortality, and growth patterns, as well as the influence of slope and aspect on regeneration outcomes.

Low-severity fires were found to promote dense regeneration but also increase competition and mortality, while high-severity fires resulted in lower seedling density yet facilitated more uniform growth among survivors. Topographic features modulated fire behavior and post-fire recovery, with medium slopes supporting optimal regeneration, steep slopes acting as natural firebreaks, and south-facing slopes exhibiting water stress-related challenges.

The recovery trends observed in low to moderate severity zones underscore the potential for natural regeneration in areas where fire intensity remains manageable. However, high severity zones face significant barriers to recovery, emphasizing the need for targeted interventions, such as soil stabilization, reseeding, and the restoration of essential ecosystem functions.

In light of the increasing frequency and intensity of wildfires driven by climate change, this study underscores the importance of integrating fire severity and landscape features into adaptive forest management strategies. These findings provide a foundation for developing context-specific interventions that balance natural recovery processes with active restoration efforts, ultimately enhancing the resilience and sustainability of Mediterranean forest ecosystems.

Références bibliographiques

1. Alexandrian, D., Esnault, F., & Calabri, G. (1999). Forest fires in the Mediterranean area. *Unasylva*, 197(50), 35–41.
2. Baeza, M. J., De Luis, M., Raventós, J., & Escarré, A. (2006). Fire risk and vegetation structural dynamics in Mediterranean shrubland. *Plant Ecology*, 187(2), 189–201.
3. Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., & Whittaker, J. B. (2002). Herbivory in global climate change research: direct effects of

rising temperature on insect herbivores. *Global Change Biology*, 8(1), 1–16. https://doi.org/10.1046/j.1365-2486.2002.00451.x

4. Belgherbi, B. (2002). *Intégration des données de télédétection et des données multisources dans un système d'information géographique (SIG) pour la protection des forêts contre les incendies (cas de la forêt de Guetarnia-Ouest d'Algérie)* [Magister's thesis, University of Tlemcen, Algérie]. P. 217.
5. Belgherbi, B., Benabdeli, K., & Mostefai, K. (2018). Mapping the risk of forest fires in Algeria: Application of the forest of Guetarnia in Western Algeria. *Ekológia* (Bratislava), 37(3), 289–300. https://doi.org/10.2478/eko-2018-0022
6. Benbakkar, H. A., Souidi, Z., Kattar, S., & Bento Gonçalves, A. J. (2024). Spatio-temporal analysis and risk management of forest fires (West Algerian region). *Folia Forestalia Polonica*, 66(4), 285–300. https://doi.org/10.2478/ffp-2024-0021
7. Boukerker, H. (2016). La forêt algérienne face aux feux : proposition d'un dispositif de prévention et de lutte. Journal Algérien des Régions Arides, 13 (Numéro spécial), 69–81. https://www.asjp.cerist.dz/en/article/77739
8. Certini, G. (2005). Effects of fire on properties of forest soils: a review. *Oecologia*, 143(1), 1–10. https://doi.org/10.1007/s00442-004-1788-8
9. Chander, G., Markham, B. L., & Helder, D. L. (2009). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment*, 113(5), 893–903. https://doi.org/10.1016/j.rse.2009.01.007
10. Chen, J., Zhu, X., Vogelmann, J. E., Gao, F., & Jin, S. (2011). A simple and effective method for filling gaps in Landsat ETM+ SLC off images. *Remote Sensing of Environment*, 115(4), 1053–1064. https://doi.org/10.1016/j.rse.2010.12.010
11. Cherki, K. & Gmira, N. (2013). Dynamique de régénération post-incendie et sévérité des incendies dans les forêts méditerranéennes : cas de la forêt de la Mâamora, Maroc Septentrional. *Revue d'Écologie (La Terre et la Vie)*, 68(3–4), 243–266. https://www.persee.fr/doc/revec_0249-7395_2013_num_68_3_1699
12. Dalloni, M. (1953). *La limite du Tertiaire et du Quaternaire dans le nord-ouest de l'Algérie et des contrées voisines*. Acte IV^{e} Congrès International Quatrenaire, 1,19−28.
13. El Bouhissi, M., Ghefar, M., Bouidjra, S. E. B., & Benabdeli, K. (2024). Assessing fire risk using the FMECA method in southern Sidi Bel Abbes (Western Algeria). *Agriculture and Forestry Journal*, 7(2) : 73–82. https://doi.org/10.46325/afj.v8i2.172

14. Elhadj, T., Driss, H., Belgacem, N., & Benchohra, M. (2021). Spatial analysis of the regeneration after fire in forest of Lardjem (Wilaya of Tissemsilt, Algeria). *Biodiversity Journal*, 12(4), 847–853. https://doi.org/10.31396/biodiv.jour.2021.12.4.847.853
15. FAO. (2020). *Évaluation des ressources forestières mondiales 2020* - Principaux résultats. Rome. https://doi.org/10.4060/ca8753fr
16. Fernández-García, V., Fulé, P. Z., Marcos, E., & Calvo, L. (2019). The role of fire frequency and severity on the regeneration of Mediterranean serotinous pines under different environmental conditions. *Forest Ecology and Management*, 444, 59–68. https://doi.org/10.1016/j.foreco.2019.04.040
17. Gao, B. C., Montes, M. J., Davis, C. O., & Goetz, A. F. H. (2009). Atmospheric correction algorithms for hyperspectral remote sensing data of land and ocean. *Remote Sensing of Environment*, 113(S1), S17–S24. https://doi.org/10.1016/j.rse.2007.12.015
18. Ghefar, M., & Bouazzaoui, A. (2021). La vulnérabilité de la forêt de Khodida (W. Sidi Bel Abbès) face aux incendies. Annales de la Recherche Forestière en Algérie, 11(2), 62–67. https://asjp.cerist.dz/en/article/163757
19. Ghorbanzadeh, O., Blaschke, T., Gholamnia, K., & Aryal, J. (2019). Forest fire susceptibility and risk mapping using Social/Infrastructural vulnerability and environmental variables. *Fire*, 2(3), 50. https://doi.org/10.3390/fire2030050
20. Haddouche, I., Benhanifia, K., & Gacemi, M. (2011). Analyse spatiale de la régénération forestière post-incendie de la forêt de Fergoug à Mascara, Algérie. *Bois & Forêts des Tropiques*, 307(307), 23–31. https://doi.org/10.19182/bft2011.307.a20478
21. Keeley, J. E. (1986). Resilience of Mediterranean shrub communities to fires. *Fire Ecology and Management in Mediterranean climate Ecosystems*, 95–112.
22. Key, C. H., & Benson, N. C. (2006). *Landscape assessment (LA): sampling and analysis methods. In Firemon: Fire effects monitoring and inventory system*. General Technical Report RMRS GTR 164 CD. USDA Forest Service.
23. Lentile, L. B., Holden, Z. A., Smith, A. M. S., Falkowski, M. J., Hudak, A. T., Morgan, P., Gessler, P. E., & Benson, N. C. (2006). Remote sensing techniques to assess active fire characteristics and post fire effects. *International Journal of Wildland Fire*, 15(3), 319–345. https://doi.org/10.1071/WF05097
24. Madoui, A., Catry, F. X., & Kaabeche, M. (2016). Wildfire effects on Pinus halepensis Mill. plantations in a semi-arid region of north-eastern Algeria. A case study of Zenadia forest, Sétif. *Ecologia Mediterranea*, 42(1), 79–92. https://doi.org/10.3406/ecmed.2016.1234

25. Mauri, E. & Pons, P. (2019). *Handbook of Good Practices in Post-wildfire Management*. 2nd ed., Anifog Project I+D+I CGL2014-54094-R, Universitat de Girona, p. 169.
26. Morgan, P., Keane, R. E., Dillon, G. K., Holden, Z. A., & Karau, E. C. (2014). Challenges of assessing fire and burn severity using field measures, remote sensing and modelling. *International Journal of Wildland Fire*, 23(8), 1045–1060. https://doi.org/10.1071/WF13058
27. Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., & Syphard, A. D. (2014). Learning to coexist with wildfire. *Nature*, 515(7525), 58–66.
28. Pausas, J. G., & Keeley, J. E. (2009). A burning story: The role of fire in the history of life. *BioScience*, 59(7), 593-601. https://doi.org/10.1525/bio.2009.59.7.10
29. Pausas, J. G., & Keeley, J. E. (2014). Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. *New Phytologist*, 204(1), 55–65. https://doi.org/10.1111/nph.12921
30. Pausas, J. G., & Vallejo, V. R. (1999). The role of fire in European Mediterranean ecosystems. *In Ecological Studies* (Vol. 137, pp. 3–16). Springer.
31. Pimont, F., Dupuy, J.-L., Rigolot, É., & Duché, Y. (2014). Les effets du passage d'un feu dans un peuplement arboré : Synthèse des connaissances et applications pour le gestionnaire forestier méditerranéen. *Forêt Méditerranéenne*, 35(3), 253-266.
32. Rafa, A. (2017). *Analyse du bilan des incendies de forêts dans la Wilaya de Sidi Bel Abbès durant la période 2010-2016*. [Master's thesis, University of Tlemcen], p. 142.
33. Rodríguez-García, E., Santana, V. M., Alloza, J. A., & Vallejo, V. R. (2022). Predicting natural hyperdense regeneration after wildfires in Pinus halepensis (Mill.) forests. *Forest Ecology and Management*, 512, 120164. https://doi.org/10.1016/j.foreco.2022.120164
34. Rodrigo, A., Retana, J., & Pico, X. (2004). Direct regeneration is not the only response of Mediterranean forests to fire. *Journal of Vegetation Science*, 15(1), 13–20. https://doi.org/10.1111/j.1654-1103.2004.tb02232.x
35. Shakesby, R. A., & Doerr, S. H. (2006). Wildfire as a hydrological and geomorphological agent. *Earth Science Reviews*, 74(34), 269 307. https://doi.org/10.1016/j.earscirev.2005.10.006
36. Tatar, H. (2012). Production forestière, exploitation et valorisation en Algérie. *Forêt méditerranéenne*. T.XXXIII, n°4, 2012, pp. 361-368.
37. Vennetier, M. (2020). Quelques aspects méconnus de la régénération du pin d'Alep après incendie. *Forêt Méditerranéenne*, 41(2), 101–120. https://hal.science/hal-03096312/

38. Viedma, O., Moity, N., & Moreno, J. M. (2015). Changes in landscape fire-hazard during the second half of the 20th century: Agriculture abandonment and the changing role of driving factors. *Agriculture, Ecosystems & Environment*, 207, 126–140. https://doi.org/10.1016/j.agee.2015.04.011
39. Zhu, Z., & Woodcock, C. E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment*, 118, 83–94. https://doi.org/10.1016/j.rse.2011.10.028