KARADENİZ TECHNICAL UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF FOREST ENGINEERING

ANALYZING LONG-TERM POST-FIRE VEGETATION RECOVERY IN RELATION TO FIRE SEVERITY IN THE MEDITERRANEAN REGION: A CASE STUDY IN TÜRKİYE AND SPAIN

MASTER'S THESIS

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FOREWORD

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Sadiq ZEYNALOV

Trabzon, 2024

THESIS STATEMENT

I hereby declare that I have completed this study titled "Analyzing Long-Term Post-Fire Vegetation Recovery in Relation to Fire Severity in the Mediterranean Region: A Case Study in Türkiye and Spain", which I have submitted as my Master's Thesis, from beginning to end under the responsibility of my advisor Assoc. Prof. Kadir Alperen COŞKUNER, that I have collected the data/samples myself, that I have performed the analyses that I have fully indicated the information I have received from other sources in the text and bibliography, that I have acted in accordance with scientific research and ethical rules throughout the study process, and that I accept all legal consequences in case the contrary occurs.

Sadiq ZEYNALOV

TABLE OF CONTENT

Page No

FOREWORD III
THESIS STATEMENT IV
TABLE OF CONTENT V
SUMMARY VII
ÖZET VIII
LIST OF FIGURES IX
LIST OF TABLES X
ACRONYMS AND ABBREVIATIONS XI
1. GENERAL INFORMATION 1
1.1. Introduction 1
1.2. Literature Review 3
1.2.1. Fire and Its Ecological Impacts 3
1.2.2. Remote Sensing Usage in Post Fire Analysis 6
1.2.3. Review of Previous Studies in Forest Fire Analysis 8
2. MATERIALS AND METHODS 12
2.1. Study Areas 12
2.1.1. Moratalla-Murcia, Spain 12
2.1.2. Moratalla fire 1994, Spain 14
2.1.3. Marmaris - Çetibeli, Türkiye 16
2.1.4. Marmaris -Çetibeli Fire in 1996, Türkiye 18
2.2 Data Sources Preprocessing of Satellite Images 20
2.2.1. Remote Sensing Data 20
2.2.2. Data Exclusion 20
2.2.3. Data Acquisition Dates 21
2.2.4. Climate Data 22
2.3. Data Processing and Calculation Steps 23
2.3.1. Normalized Burn Ratio (NBR) 23
2.3.2. Differenced Normalized Burn Ratio (dNBR) 24
2.3.3. Classification of Fire Severity 24

2.3.4. Calculation of NDVI Values........25
2.3.5. Calculation of NDMI Values........26
2.4. Statistical Analysis........26
3. RESULTS........28
3.1. The results of the 1994 Moratalla Fire in Spain........28
3.1.1. Moratalla fire NDVI and NDMI results........29
3.2. The Results of the 1996 Çetibeli Fire in Türkiye........35
3.3. The Results of Correlation Analysis Between Post Fire Vegetation Recovery and Climatic Factors........42
3.4. Trend Analysis of Climate Variables........45
4. DISCUSSION........48
4.1. Fire Severity and Vegetation Recovery........48
4.2 Post Fire recovery and Climate Variables........50
5. CONCLUSION AND RECOMMENDATIONS........52
6. REFERENCES........54
RESUME

Master’s Thesis

SUMMARY

ANALYZING LONG-TERM POST-FIRE VEGETATION RECOVERY IN RELATION TO FIRE SEVERITY IN THE MEDITERRANEAN REGION: A CASE STUDY IN TÜRKİYE AND SPAIN

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Karadeniz Technical University
The Graduate School of Natural and Applied Sciences
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Supervisor: Assoc. Prof. Kadir Alperen COŞKUNER
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This thesis investigates the impact of burn severity and climatic factors on post-fire vegetation development in Mediterranean ecosystems. The post-fire vegetation recovery and moisture changes in areas affected by the 1994 Moratalla fire in Spain and the 1996 Marmaris-Çetibeli fire in Türkiye were analyzed using the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI). Satellite images were utilized to assess vegetation recovery from the time of the fires until 2023.

The results indicate that vegetation in areas with high burn severity generally showed faster recovery, with average NDVI values in the Çetibeli site reaching pre-fire levels after 17 years, and in the Moratalla site after 15 years. A significant positive correlation was found between NDVI and NDMI values in both study areas.

The relationship between post-fire vegetation development and climatic factors was also examined. The findings reveal a significant positive correlation between post-fire NDVI values and the amount of precipitation during the growing season (March-August) following the Moratalla fire, which occurred in the semi-arid region of Spain. These results highlight the crucial role that precipitation plays in the recovery of vegetation in semi-arid regions.

Keywords: Forest fires**,** NDVI, NDMI, vegetation recovey, climate

Yüksek Lisans Tezi

ÖZET

YANMA DERİNLİĞİNE BAĞLI OLARAK AKDENİZ BÖLGESİNDE UZUN DÖNEMLİ YANGIN SONRASI VEJETASYON GELİŞİMİNİN ANALİZİ: TÜRKİYE VE İSPANYA ÖRNEĞİ

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Bu tez, yanma derinliği ve iklim faktörlerinin Akdeniz ekosistemlerindeki yangın sonrası bitki örtüsü gelişimi üzerindeki etkisini araştırmaktadır. İspanya'da 1994 Moratalla yangınından ve Türkiye'de 1996 Marmaris-Çetibeli yangınından etkilenen alanlarda yangın sonrası bitki örtüsünün gelişimi ve nem değişiklikleri, Normalleştirilmiş Fark Bitki Örtüsü İndeksi (NDVI) ve Normalleştirilmiş Fark Nem İndeksi (NDMI) kullanılarak analiz edilmiştir. Uydu görüntüleri, yangın tarihlerinden 2023 yılına kadar bitki örtüsünün iyileşmesini değerlendirmek için kullanılmıştır.

Sonuçlar, yüksek yanma derinliği olan alanlarda bitki örtüsünün genellikle daha hızlı gelişim gösterdiği ve Çetibeli yangın alanında ortalama NDVI değerlerinin yangından 17 yıl sonra, Moratalla yangın alanında ise ise 15 yıl sonra yangın öncesi seviyelere ulaştığını göstermiştir. Her iki çalışma alanında da NDVI ve NDMI değerleri arasında anlamlı pozitif bir korelasyon bulunmuştur.

Yangın sonrası bitki örtüsü gelişimi ile iklim faktörleri arasındaki ilişki de incelenmiştir. Bulgular, İspanya'nın yarı kurak bölgesinde yer alan Moratalla yangını sonrası, yangın sonrası NDVI değerleri ile büyüme sezonu (Mart-Ağustos) boyunca düşen yağış miktarı arasında anlamlı pozitif bir korelasyon olduğunu ortaya koymaktadır. Bu sonuçlar, yarı kurak bölgelerde bitki örtüsünün iyileşmesinde yağışın kritik rol oynadığını vurgulamaktadır.

Anahtar kelimeler: Orman yangınları, NDVI, NDMI, vejetasyon gelişimi, iklim

LIST OF FIGURES

Page No

Figure 1. The Study area of Moratalla Fire in Murcia, Spain 12

Figure 2. Land cover classification map of Moratalla fire (2009).....................................13

Figure 3. Moratalla False Color image (a: pre-fire image (13.06.1994),
b: post-fire image (31.07.1994) 15

Figure 4. The Study area of Çetibeli fire in Marmaris-Mugla, Türkiye 16

Figure 5. Land cover classification map of Çetibeli fire (2009) 17

Figure 6. Çetibeli False Colour image (a: pre-fire image (13.06.1996,
b: post-fire image (01.09.1996) 19

Figure 7. Fire severity (dNBR) map of Moratalla fire..28

Figure 8. NDVI trends of Moratalla fire 31

Figure 9. NDVI maps of Moratalla fire 32

Figure 10. NDMI trends of Moratalla fire...33

Figure 11. NDMI maps of Moratalla fire 34

Figure 12. Fire Severtiy (dNBR) map of Çetibeli fire..35

Figure 13. NDVI trends of Çetibeli fire 38

Figure 14. NDVI maps of Çetibeli fire 39

Figure 15. NDMI trends of Çetibeli fire 40

Figure 16. NDMI maps of Çetibeli fire...42

Figure 17. Precipitation pattern trend (Moratalla)..45

Figure 18. Mean temperature of spring months (Moratalla)...46

Figure 19. Trend analysis growing season precipitation
and NDVI mean (Moratalla) 46

Figure 20. Precipitation patterns trends (Çetibeli)..47

Figure 21. Mean temperature of spring months (Çetibeli)...47

Figure 22. Trend analysis of mean April temperature and mean NDVI (Çetibeli) 48

Figure 23. Trend analysis of first half year precipitation and mean NDVI (Çetibeli).........48

LIST OF TABLES

Page No

Table 1. Land cover percentage of Moratalla burned area (Coperniscus Classification 2019)....................14
Table 2. Land cover percentage of Çetibeli (2019) 18
Table 3. Dates of satellite images for Moratalla fire....................21
Table 4. Dates of satellite images for Çetibeli fire 22
Table 5. Fire severity classification (Key & Benson, 2006) 24
Table 6. Burned Area and Percentage of Each Fire Severity Class in Moratalla, Spain......29
Table 7. Long – term NDVI and NDMI values of Moratalla fire....................30
Table 8. Burned Area and Percentage of Each Fire Severity Class in Çetibeli, Türkiye 36
Table 9. Long – term NDVI and NDMI results of Çetibeli fire 37
Table 10. Correlation matrix of Moratalla fire 43
Table 11. Correlation matrix of Çetibeli fire 44

ACRONYMS AND ABBREVIATIONS

GIS	: Geographic Information Systems
RS	: Remote Sensing
PVR	: Post-fire vegeation recovery
NDVI	: Nornalized Difference Vegetation Index
NDMI	: Normalized Diffrence Moisture Index
EVI	: Enhanced Vegetation Index
NBR	: Normalized Burn Ratio
dNBR	: Diffrenced Normalized Burn Ratio
GS	: Growing season
FHY	: First - half year
PREC	: Precipitation
T	: Temperature

1. GENERAL INFORMATION

1.1. Introduction

Forest fires, while often perceived as destructive forces, play a crucial role in maintaining the health and diversity of ecosystems. In many ecosystems in the world, fire forms an inseparable part of the system. Regular wildfires are needed for the continuity of African savannas, Mediterranean maquis or pine forests in many regions of the world. In these ecosystems, called fire-dependent ecosystems, many species adapt to the existing fire regime and maintain their continuity in the system. Wildfires, fires, which change the ecosystem structure, species composition and richness and ensure its continuity (Bilbao et al., 2020). Fire has a wide range of effects in the forest. In the simplest terms, fire burns, spreads and releases energy. These effects have important ecological and economic consequences. The most important effect of fire in forests is that it burns organic material to ashes (Bodí et al., 2014).

Fire is nature's way of clearing away dead litter from forest floors. This returns important nutrients to the soil, allowing plants and animals to start a new, healthy life. When dead or decaying plants begin to accumulate in the soil, they can block nutrients from soil organisms or prevent soil animals from accessing the soil. This coating of dead organic matter can also suffocate the growth of smaller or new plants. Moreover, the residual mineral substances that occur after the fire cause chemical effects. The relations of these substances with the soil produce important results (Bilgili, 2014).

Remote Sensing (RS) and Geographic Information Systems (GIS) provide a superior approach to fire monitoring and assessment. Especially in the prevention, damage analysis and monitoring stages, images obtained by remote sensing satellites provide a synoptic data set containing rich spectral and spatial information (Chuvieco et al., 2020). When evaluated in terms of forest areas with high fire risk factors, the ability of a geographic information system to process key features such as meteorological, physical, ecological and logistic data together creates the opportunity for the development of prevention and early intervention plans, as well as for the early analysis of damage that will occur as a result of a possible fire (Gai et al., 2011).

Post fire vegetation recovery can be assessed by using different indices through RS techniques. In literature, various of methods have been used before. The Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973), the Enhanced Vegetation Index (EVI), (Wardlow & Egbert, 2010) and the Normalized Burn Ratio (NBR) are the NIR-based spectral indices that are most frequently used to monitor PVR among those derived from RS imagery (Stankova, 2023). NDVI and EVI are used in scenarios where natural variability is essential due to their high sensitivity to seasonal and biophysical variations in vegetation changes. Despite their tendency to saturate over dense forests and their inefficiency in measuring the species composition or the structure of the forest, they serve as a good proxy for vegetative regrowth. Generally used to assess the level of burn severity, NBR is also a useful tool for assessing long-term vegetation regeneration and is currently being reconsidered as a measure for post-fire recovery (Adagbasa et al., 2020; Pérez-Cabello et al., 2021).

Many studies have been done regarding post fire vegetation recovery using RS (Kurbanov et al., 2022). Those studies mainly focus on the relationship between fire severity and vegetation recovery rate, as well as recovery driven patterns. The monitoring of post-fire vegetation recovery is important since it provides valuable data for assessing ecosystem resilience, determining landscape dynamics, and forest management (Pérez-Cabello et al., 2021).

The use of remote sensing techniques to study post-fire vegetation recovery has been the subject of numerous studies. But most of these studies have concentrated on short-term recovery, which usually lasts for a few years after the fire incident. The entire trajectory of vegetation regrowth and ecosystem stabilization is frequently missed by these studies, despite the fact that they offer insightful information about the immediate effects of fire and the early phases of ecological recovery (De Luca et al., 2022; Meng et al., 2018).

There are some studies available in the literature to monitor post fire recovery in Türkiye (Ercan & Uygunol, 2022; Güney et al., 2023; Sabuncu & Özener, 2019) and Spain (Viana-Soto et al., 2017). These studies cover nearly short periods (5-10 years) however, there is no study available in the literature to evaluate long term post-fire vegetation recovery considering the effects of fire severity and long-term climatic effects in different Mediterranean ecosystems.

The objective of the study is to provide a more thorough understanding of how fire severity affects vegetation recovery over time by broadening the temporal scope of the analysis in two different Mediterranean ecosystems. This long-term view is essential for seeing patterns that shorter-term studies might miss, like delayed recovery, altered recovery rates, or vegetation returning to pre-fire levels.

In this study 1994 Moratalla fire in Spain and the 1996 Marmaris - Çetibeli fire in Türkiye were analysed. Normalized Burn Ratio (NBR) was used to measure the severity of the fire. NDVI and NDMI values up to 2023 to were analysed the vegetation recovery over almost thirty years. In order to comprehend the dynamics of recovery, the analysis was carried out across several fire severity classes. To investigate their impact on post-fire recovery, we also analysed at these vegetation indices and different climatic factors.

This study stands apart in that it covers a longer period of time, allowing to observe long-term recovery patterns that are crucial for shaping strategies for sustainable forest management and restoration and to improve our knowledge of the dynamics of post-fire vegetation and provide guidance for future land management and conservation efforts in areas that are vulnerable to wildfires. Moreover, this research has potential contributions in advance knowledge by providing insights into the long-term efficacy of natural regeneration processes and the resilience of various vegetation types.

1.2. Literature Review

1.2.1. Fire and Its Ecological Impacts

A fire needs three different parameters to start and continue. These parameters; heat, fuel and oxygen. If any of these parameters are not included in the fire triangle, a fire event will not occur. For forest fires to start, certain parameters must be present. The ignition and spread of fire, fuel moisture, weather conditions, type of fuel and topography play an important role in starting the fire. While fuel moisture and weather conditions of the region are associated with temporal and short-term variation in forest fire danger, the type of fuel and topography are associated with spatial and long-term variation (Sabuncu & Özener, 2019).

In another words, the fire triangle represents the three elements that cause fire. When one of these elements is removed, the fire will go out. Oxygen is a component of air necessary to burn a combustible substance and is readily available in the natural environment. Weather parameters plays an important role in shaping the spread of forest fires. Heat is the energy required to mix with oxygen in the air to form a vapor to ignite a combustible material. Combustible material can be heated in many ways to reach its ignition point. Combustible material is any flammable material or vegetation that is ready to burn. Fuel type, amount, structure and moisture content will affect the nature of fire spread (Plana Bach & Serra Davos Forest, 2016).

Ground fires are those that spread and consume the organic layer above the mineral soil, usually without flaming. These fires spread at a very slow rate, so they do not pose a safety risk. Given that they can last for long periods of time, emit large amounts of smoke into the atmosphere, and have a strong and negative health impact on the soil and organisms near the ground, their importance cannot be overstated. Peat lands are prone to sustaining this type of fire spread (Viegas, 2011).

Surface fires are those that spread and consume vegetation above ground, such as forest litter, herbaceous vegetation, shrubs, and small trees. These fires typically spread with a flaming fire-front that consumes the finer parts of the vegetation, primarily dead material with a low moisture content. This type of fire transmission is the most typical and well-studied mode. Crown fires are fires that move by the green canopies of trees and shrubs, typically with the help of a surface fire that started at ground level. These fires can spread quickly, release huge quantities of energy, and destroy vast tracts of forest, all of which have a significant ecological impact. Spot fires are caused by consuming particles released during the combustion of a variety of fuels, which land on adequate fuel beds and cause new ignitions. Spot fires are extremely dangerous because they can ignite new fires behind a fire suppression team, which may be caught off guard between two fire fronts (Viegas, 2011).

The term "fuel" describes the kind and quantity of vegetation that can be burned. The amount of biomass found in the three main vegetation strata—trees, shrubs, and herbaceous vegetation—as well as its moisture content determines how a fire starts and spreads. The moisture content of fuel is determined by the biomass's moisture content, flammability (ease of lighting), and combustibility (ease of burning), all of which differ depending on the species. The most destructive forest fires occur in dense forests with high strata continuity during the dry season, which stimulates crown fires, which occur when a fire burns uncontrolled in the tree and shrub canopy. Under the same forest conditions, fires primarily occur during the wet season (Plana Bach & Serra Davos Forest, 2016).

Fire is an innate phenomenon that has been present for millions of years. Current perspectives on fire ecology view them as dynamic ecological processes that are largely shaped by human activity and have evolutionary ramifications. The aim of fire ecology is to comprehend the variety of ways that fire impacts terrestrial species and ecosystems. Furthermore, fire regimes have a wide-ranging impact on populations, communities, and ecosystems (McLauchlan et al., 2020). For many forest ecosystems to function, fire is a necessary and natural component. Fire has been used by humans to manage their land for thousands of years. One of the natural forces that has shaped plant communities over time is fire, which is also a vital natural process that keeps some ecosystems healthy (Nasi et al., 2002). It is now recognized that fire is a recurrent process that produces fire regimes that directly affect the environment and serve as selection forces, affecting the characteristics of species over the course of entire generations (He et al., 2019).

Over half a million hectares of Europe's forested areas are destroyed by fires, which average 70,000 per year. The greatest concentration of fire activity and fire effects is found in the Mediterranean region of Europe. Approximately, 70% of all fires and 85% of all burned land in Europe occur in this region. Though the frequency of fires peaks three times a year—in the winter in mountainous areas, in the spring due to agricultural practices, and in the summer due to high temperatures and summer drought—the majority of fire damage occurs during the summer, specifically in the months of July, August, and September (European Environment Agency, 2010)

Forest fire management and research are complex issues that necessitate a multidisciplinary approach. Given the large number of processes and factors that occur during a forest fire, which spans several orders of magnitude in space and time, scientists from various specialized backgrounds are needed to better understand and manage forest fires (Viegas, 2011). Regrettably, forest fires are typically only noticed after they have consumed a sizable region, which makes controlling and extinguishing them difficult or even unfeasible at times. Devastating loss and irreversible harm to the atmosphere and environment are the outcomes (Alkhatib, 2014). The issue with forest fires is that they typically occur in isolated, neglected, or unmanaged forests that are full of trees, parched and dry wood, leaves, and other materials that can catch fire. These components combine to create a highly flammable substance that is ideal for starting a fire in the first place and supplying fuel for it in later phases (Alkhatib, 2014).

One of the most significant ecological consequences of burning is the increased likelihood of more fires in the years to come as fallen trees expose the forest to sunlight-induced drying and increase the fuel load by attracting more species that can catch fire, like pyrophytic grasses. Recurrent burning has negative effects as it contributes significantly to the decline in biodiversity in rainforest ecosystems. Insect colonization and infestation can occur after fires, upsetting the natural equilibrium (Nasi et al., 2002).

Traditionally, studies of above-ground fire effects focused on plant mortality and regeneration. Fire has a wide impact on aboveground ecosystems, affecting everything from plant growth to global climate. More research is needed to better understand the feedback mechanisms that contribute to increased fire activity, in addition to the timing and persistence of plant population traits and community processes following fires (McLauchlan et al., 2020). Additionally, forest fires can have impact on soil texture, soil water repellency. organic matter, nutrition dynamics, biological properties such as microorganisms and invertebrates (Verma & Jayakumar, 2012). When comparing nearby slightly or moderately burned soil to severely burned soil under concentrated fuel, the changes in soil color and texture are most obvious (Zavala et al., 2014).

1.2.2. Remote Sensing Usage in Post Fire Analysis

Products from remote sensing (RS) offer global data in a range of spectral regions and spatial resolutions. Their methodical observation of the Earth's surface makes multitemporal analysis possible. Furthermore, they gather data without resorting to destructive sampling. Since the early 1970s, RS data have been widely used in fire-related research and management, which can be attributed to all of these properties. The early applications were primarily concerned with aerial photography visual analysis. Satellite data has been used for many stages of fire management since the Landsat satellite was launched in 1972. These stages include assessing fire danger, locating active fires, and analyzing the effects of fire and vegetation recovery. (Chuvieco et al., 2020).

The temporal progression of forest fires reveals significant damage inflicted upon both the immediate ecosystem and its surrounding environment. Consequently, effective monitoring and control of forest fires emerge as imperatives. Geographic Information Systems (GIS) and RS offer indispensable tools for this purpose. Through the application of GIS and RS, spatial data pertaining to numerous forest fires can be systematically catalogued, facilitating detailed examinations of the extent of devastation incurred. Additionally, these methodologies enable decision support analyses, including the identification of regions prone to forest fires, as well as predictive modelling to anticipate the potential trajectory and spread of future fire incidents. By leveraging such technological advancements, informed strategies for forest fire management and mitigation can be developed (Şirin & Ekiz, 2021). In comparison to extensive and labour-intensive field campaigns, RS techniques are an affordable manner to monitor post-fire ecosystem recovery in terms of time and costs (Fernández-Guisuraga et al., 2019).

Traditionally, fieldwork or aerial vehicles have been used to assess the severity of fires. This has been followed by a manual mapping process that categorizes the damage caused by the fire. But ever since the Landsat satellite program was launched in 1972, it has become possible to periodically estimate the severity of fires at a significantly reduced cost (Francos & Lemus-Canovas, 2021). Specifically designed to assess wildfire intensity, the Normalized Burn Ratio (NBR) is one of the most widely used indices to measure the severity of a fire. But the ability to compute the difference between pre- and post-fire NBRs, or the differenced Normalized Burn Ratio (dNBR), is essential for accurately quantifying the severity of burns. This method has been tested in multiple studies with positive outcomes (Key & Benson, 2006).

Alongside post fire analysis, pre fire actions such as active fire detection can be done by using remote sensing techniques. However, their accuracy may vary depending on land cover types and satellite products were used. Coskuner (2022) has evaluated the performance of MODIS and VIIRS S-NPP active fire/hotspot products for detecting fires in various land cover types in Türkiye using ground-based fire data from 2015 to 2019. The overall accuracy of MODIS in detecting ground-based fires ranged from 0.6% to 16.6%, while VIIRS S-NPP ranged from 1.3% to 25.6%, depending on the land cover type. Detection rates for both MODIS and VIIRS S-NPP increased with the size of the fire. Smaller fires, particularly those less than 10 hectares, were less likely to be detected. The study highlighted significant limitations in using MODIS and VIIRS S-NPP for wildfire detection under closed canopy conditions, where dense vegetation can obscure fire signals. The results indicated that the performance of these products might vary by region and vegetation type, suggesting the need for further studies in different wildfire-prone areas. Overall, while both MODIS and VIIRS S-NPP show some capability in detecting larger fires, their effectiveness is limited for smaller fires and under dense canopy cover. Further research is recommended to enhance fire detection methodologies in diverse geographical locations (Coskuner, 2022).

Fuel moisture content, fuel type mapping, burned area, active fire detection, and vegetation recovery are the parameters that are produced from RS imagery most frequently. Numerous studies integrate different systems and sensors, such as thermal-optical, optical-lidar, and radar, to satisfy user needs for non-fire application-specific sensors. A more thorough assessment of fire danger and fire effect has been made possible in recent years by the linking of disparate spatial and temporal scales. The growing utilisation of RS products in atmospheric and carbon models suggests an intention to enhance current models and data (Chuvieco et al., 2020).

The Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), and the Normalized Burn Ratio (NBR) are the NIR-based spectral indices that are most frequently used to monitor PVR among those derived from RS imagery. Because of their high sensitivity to seasonal and biophysical variations in vegetation changes, NDVI and EVI are utilized in situations where natural variability is crucial (Veraverbeke et al., 2012).

1.2.3. Review of Previous Studies in Forest Fire Analysis

One of the important topics in forest fire research is the theory of vegetation recovery patterns afterwards fires. Russian researchers started looking into how fire affected the ecological environment in the 1930s (Bowman, 2007). The study has done in China showed that fire promotes vegetation growth and development in fire-affected areas, maintaining vegetation index values above pre-fire levels. This is attributed to several factors such as fire burning tall trees, allowing more sunlight into low-lying areas. Also, some low-lying herbaceous plants' seeds being stimulated to grow by the fire. The same study demonstrated interesting post fire recovery results: The highest severity burned areas showed the fastest vegetation recovery in the first two years post-fire, consistent with previous research. However, it took about seven years for burned areas to fully recover to pre-fire levels (Hao et al., 2022).

It should be noted that the correlation between fire severity and post fire vegetation recovery is not always in the same direction as it can vary depending on species. According to Alba Viana-Soto and his colleagues, a significant decrease in post-fire values followed by a gradual recovery, particularly noticeable in the initial years. *Pinus nigra* and *Pinus pinaster* exhibited a faster recovery compared to *Pinus halepensis*, which showed slower regeneration. Fire severity levels significantly influence the regeneration of *Pinus* species, with higher NDVI values correlating with lower fire severity. Variations in pre-fire values among fire severity levels are attributed to the influence of other environmental factors specific to each zone. Additionally, areas characterized by higher pre-fire dryness levels tend to experience more intense burning. Short-term regeneration fluctuations may occur due to variations in image acquisition dates post-summer (Viana-Soto et al., 2017).

Species dependent recovery mode rate has been seen in another study was done by Ran Meng and his colleagues. Their study revealed notable differences in the post-fire recovery rates between pine and oak canopies. Specifically, we observed a maximum recovery rate for pine canopies of approximately 12% per year, which was nearly three times higher than that of oak canopies, averaging around 4% per year. Furthermore, the burn severity (dNBR) trend for pine stands, with a value of 0.625, was significantly greater compared to oak stands, which recorded a value of 0.425. This disparity indicates a higher level of fire resistance among pine stands. Additionally, we identified a positive linear relationship between the post-fire oak resprout rate and burn severity. The maximum resprout rate for oak trees was nearly 10% per year, suggesting a distinctive fire-adaptive strategy employed by oak trees (Meng et al., 2018).

However, sometimes fire severity can lose its impact on vegetation recovery. One of the studies in Catalonia has documented that fire severity is no longer determinant after a long period. According to Marcos Francos and his colleagues, fire severity was a factor in determining vegetation cover one and ten years after the fire. Post-fire responses are highly affected by the time of recovery, and the impact of fire is highly dependent on the fire severity over shorter terms, but after 18-years, the recovery of the vegetation was successful in all the three fire intensities studied sites (Francos et al., 2016).

Another study in Türkiye, has shown close results to the previous one. The study area was Marmaris region. According to the study before the fire in 2002, the average plant density on the land was 0.34, indicating that the vegetation was moderately healthy. Post-fire NDVI values dropped significantly to an average of 0.1, showing that the vegetation cover was nearly destroyed across the area. By 2023, the NDVI values of the burned area had increased to an average of 0.25. This indicates that the burned areas have begun to regenerate, but the plant density has not yet returned to its pre-fire levels (Siyavus and Ahmet, 2023)

Recent research into the effects of burn severity on postfire vegetation recovery and albedo in North American boreal forests has yielded important results. The study's major findings can be summarized as follows: High-severity burns resulted in the greatest initial reduction in vegetation cover, as measured by the summer Enhanced Vegetation Index (EVI). This suggests a significant immediate impact on the ecosystem's photosynthetic capacity. Areas affected by high-severity burns showed faster vegetation recovery than areas affected by low-severity burns. Within 5-8 years after the fire, EVI values in these areas had converged to 90-108% of their pre - fire levels, indicating a resilient recovery (Jin et al., 2012).

Wildfires, depending on their severity, can have long-term effects on the abundance, diversity, and density of herbaceous and woody plants. High-severity fires can significantly reduce woody plant richness, while herbaceous plants may experience changes in richness, diversity, and density for longer periods. Over time, areas affected by high-severity fires may experience a shift in vegetation composition, with shrubs becoming more dominant and tree cover decreasing. This change can lead to increased fuel continuity and higher vegetation density, which may raise the risk of future wildfires if not managed properly (Francos & Lemus-Canovas, 2021).

Burn severity has a significant impact on the ability of vegetation systems to recover to their original state. Different vegetation cover recovery patterns were observed depending on burn severity levels, with more serious burns resulting in slower recovery rates. Alfonso Fernandez-Manso and his colleagues have found that the regeneration process is strongly correlated with the type of vegetation present prior to fire. For example, the dominant species, *Pinus pinaster*, demonstrated high rates of natural regeneration. Over five years, the mean height of seedlings increased significantly, and woody species cover increased from 1.5% in the initial year after the fire to 72% in the third. The estimated resilience times for vegetation cover are 7 years for low, 13 years for moderate, and 20 years for high burn severity. These estimates are consistent with other studies on similar ecosystems (Fernandez-Manso et al., 2016).

In Mediterranean ecosystems, non-native species usually shows slow recovery rate after fire. The study has been done in the southern part of Portugal revealed that forest and shrub/herbaceous vegetation types demonstrated high recovery efficiency, especially in low to moderate severity areas. Within three years, the vegetation recovered to its pre-fire levels. Non-native eucalyptus plantations had lower recovery rates than native species. The recovery of eucalyptus was slow and did not reach pre-fire levels during the observed period.

Also, the temporal profiles of vegetation indices and climate variables like temperature and rainfall were found to be correlated by the study. Seasonal stability and intra-annual variability were noted, suggesting that the climate has an impact on the dynamics of post-fire recovery. In terms of long-term recovery rate, with the exception of those in high-severity fire categories and non-native plantations, the majority of vegetation types displayed a return to pre-fire spectral values by the end of the monitoring period. According to the study, native species are better at reestablishing ecological balance after fires (De Luca et al., 2022).

2. MATERIALS AND METHODS

2.1. Study Areas

2.1.1 Moratalla-Murcia, Spain

The study area is situated in the northwest of the province of Murcia, primarily within the Northwest Region and the municipality of Cieza and Moratalla. The study area affected 1994 fire in the province of Murcia, Spain's Sierra del Cerezo mountain range, close to the village of Moratalla (Fig. 1). At 1140 m. above sea level, the mostly southwest to northeast-oriented Sierra del Cerezo mountain range is made up of dolomitic and limestone rocks (Ruano et al., 2013; Servicio Forestal del Departamento de Agricultura, 2008).

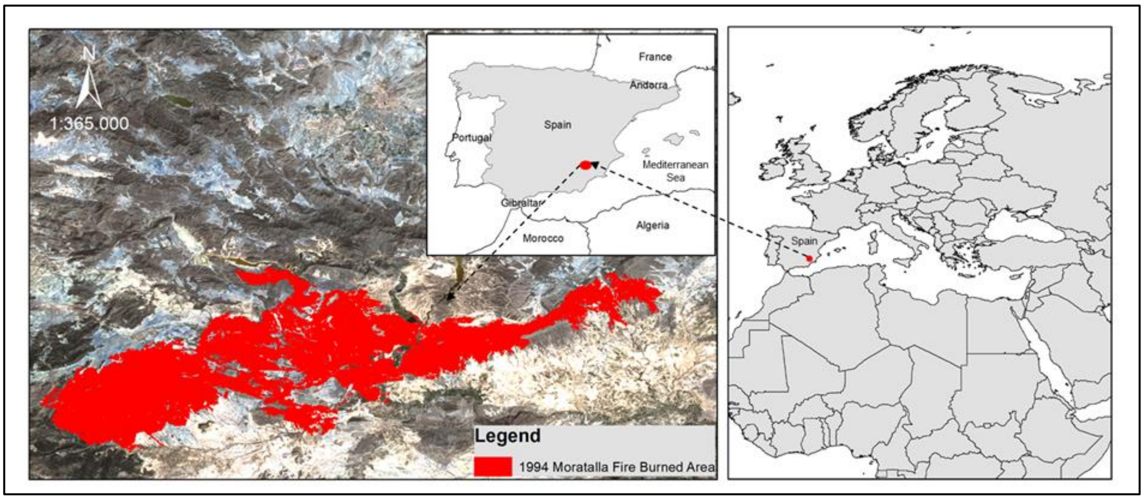

Figure 1. The Study area of Moratalla fire in Murcia, Spain.

The most common tree formations are Aleppo pine (*Pinus halepensis*) forests, whereas oak forests are less common and are mixed with pine forests rather than existing in isolation. More detailed information regarding vegetation cover is given below in Figure 2. Despite its close proximity to the Mediterranean Sea, Murcia (latitude 37"58' N, 40 metres above sea level) has cold winters and very hot summer. This region's low relative humidity and high sunshine hours are further characteristics of its climate. Rainfall during the growing season is comparatively low: the long-term average for Murcia is 131 mm, and there is no precipitation from June to August inclusive. With only 305 millimetres of rainfall annually, spring and autumn see the most rainfall (Dry, 2001).

To create an accurate land cover map, data from the Copernicus Land Cover program were utilized (URL-1). Copernicus, a program coordinated and managed by the European Commission in partnership with the European Space Agency (ESA), provides high-resolution land cover information essential for detailed environmental analysis. This data facilitated the identification and categorization of various land cover types, contributing to a comprehensive understanding of the landscape dynamics. According to the 2019 Copernicus Land Cover data, open forest type makes up 45.0% of the total area and is the most common land cover in the Moratalla region. Forest areas make up a sizable portion of the landscape when combined with other forest types (closed forest and open forest with evergreen needle leaf) Shrubland covers 25.1% of study area. (Fig. 2, Table 1).

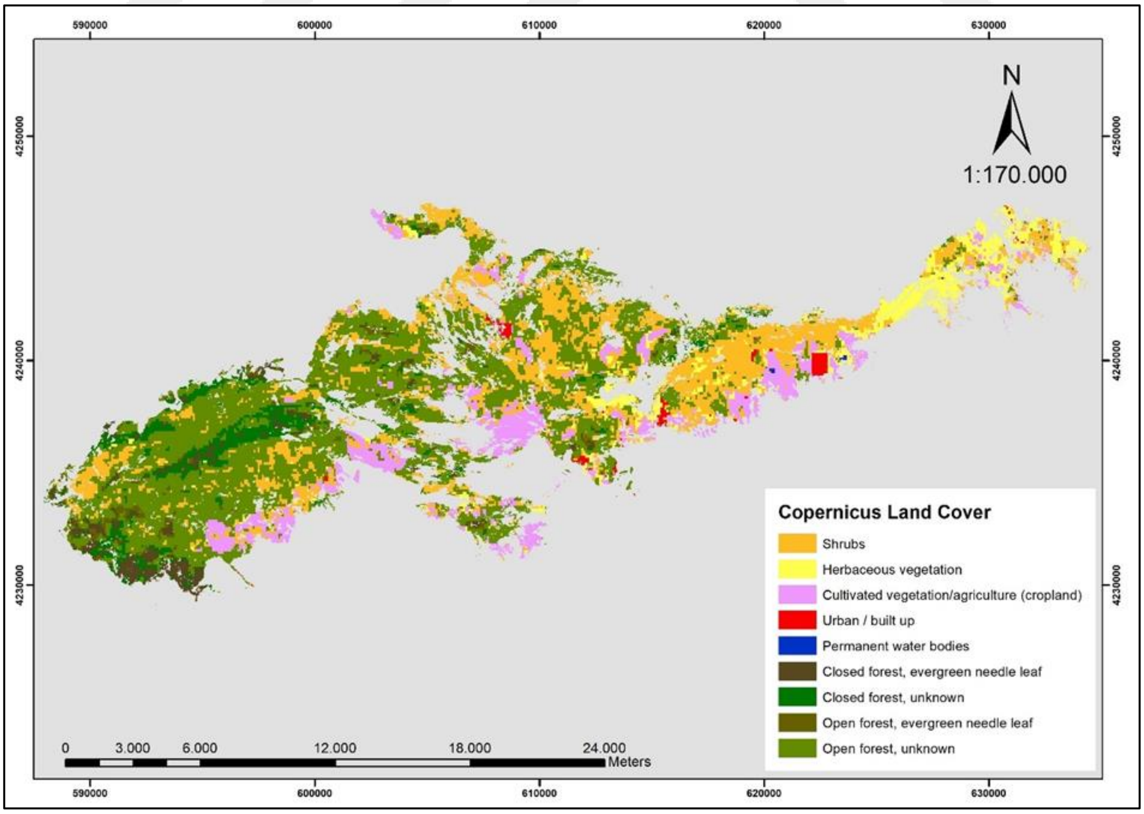

Figure 2. Land cover classification map of Moratalla burned area (2019)

Using data from the Copernicus Land Cover database, this map displays the different types of land cover in the Moratalla region (Fig 2.). Color coding of the various land cover categories facilitates identification and analysis. Below, the area of each classification is shown (Table 1).

Table 1. Land cover percentage of Moratalla burned area (Copernicus Land Cover Classification 2019)

Copernicus Land Cover	Area (Ha)	Area (%)
Shrubs	5615.5	25.1
Herbaceous vegetation	1624.9	7.3
Cultivated vegetation/agriculture (cropland)	2374.2	10.6
Urban / built up	199.5	0.9
Permanent water bodies	12.2	0.1
Closed forest, evergreen needle leaf	851.0	3.8
Closed forest, unknown	1221.8	5.5
Open forest, evergreen needle leaf	405.8	1.8
Open forest, unknown	10074.2	45.0

2.1.2. Moratalla fire 1994, Spain

On July 4, 1994, was a completely clear day dawned in the Northwest region. The meteorological department warned that during the week temperatures could reach 46º. Because of extreme high temperature and strong wind, fire started and spread to the other parts of the municipality. Since maintenance work on the wiring in the area had been completed in the previous days, the cause of the disaster could have been an electrical fault caused by the contact of a pine tree with the power lines, resulting in a spark that caused the catastrophe. At the peak of the fire's eruption, several fronts were maintained, totalling more than 90 kilometres, and many houses had to be evacuated, although fortunately, no human injuries occurred. (URL-2, URL-3). A total of nearly 22.4 thousand hectares of land area were affected (Fig 3b).

Below in figure 3, burned area of Moratalla fire has been presented by using Landsat 4-5 Thematic Mapper (TM) satellite images false color methodology. False-color maps are used to improve the visual distinction between areas that have burned and those that have not. Vegetation and burned areas can be effectively highlighted by adjusting the spectral bands, giving a clear visual depiction of the fire impact. In order to visually assess the impact of the fires and clearly delineate the burned areas false-color composite images are created for both pre-fire and post-fire conditions in the study areas. Understanding the spatial extent and severity of the fires requires an understanding of these images.

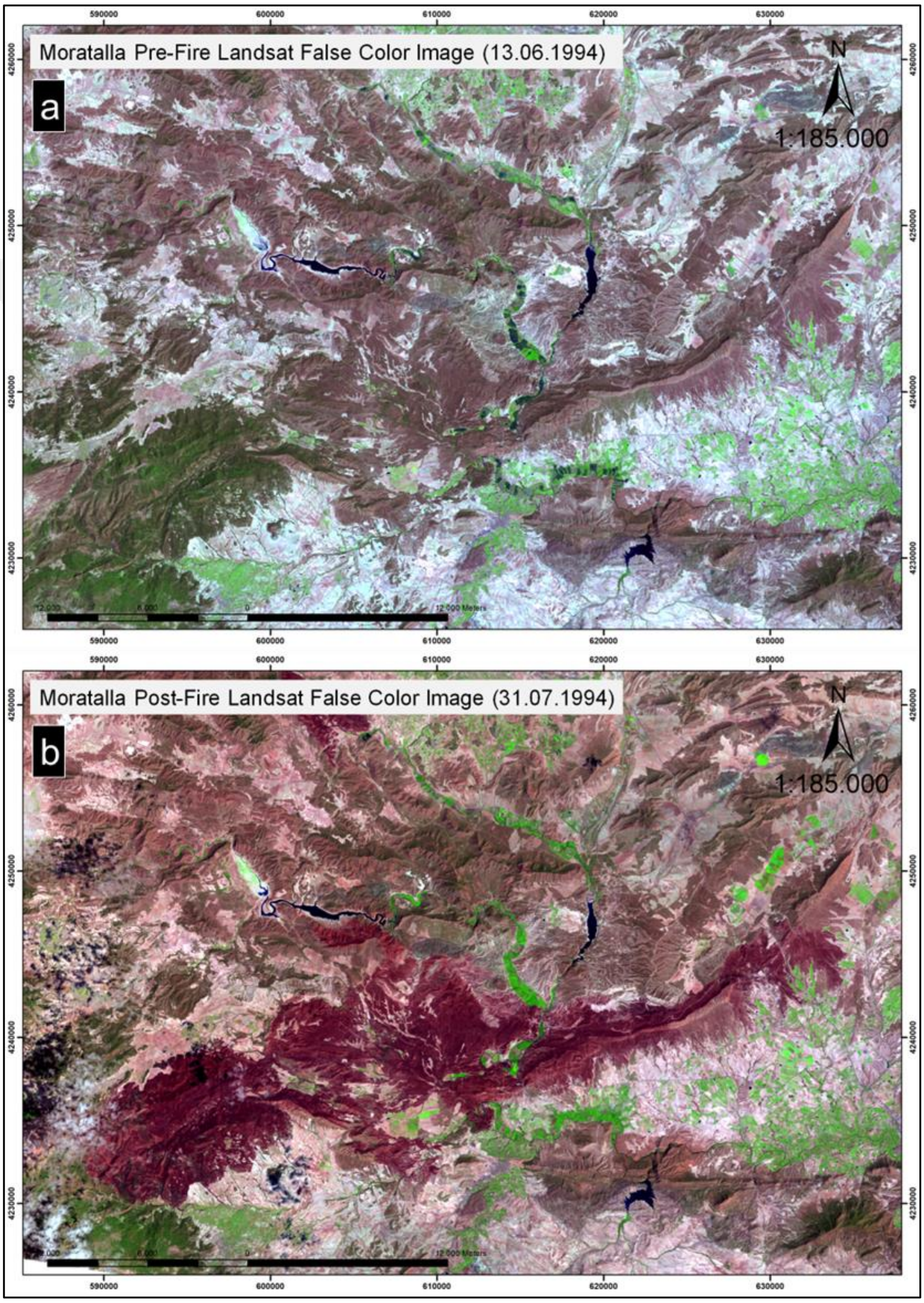

Figure 3. Moratalla Fire False Color image (a: pre-fire (13.06.1994), b: post-fire (31.07.1994))

Pre-Fire Image (Fig. 3a) present study areas prior to the fire incident. Green color in the vegetation indicate a dense and healthy cover of vegetation. It is also evident how clearly land and water are distinguished from one another, with water bodies appearing dark. Post-fire image (Fig. 3b) is captured in those images right after the fire. Shades of red and brown make the burned areas clearly visible, signifying the extent of the fire and the loss of vegetation. The extent and impact of the fire are highlighted by the contrast between the burned and unburned green areas.

2.1.3. Marmaris - Çetibeli, Türkiye

The study area is situated in Muğla, on the southern edge of the Aegean Region. The burned area is elongated from northeast to southwest and roughly one kilometer south-east of the Çetibeli district. Locations range in elevation from 10 to 600 m. from the northwest to the southeast. The location of the study area can be seen in Figure 4.

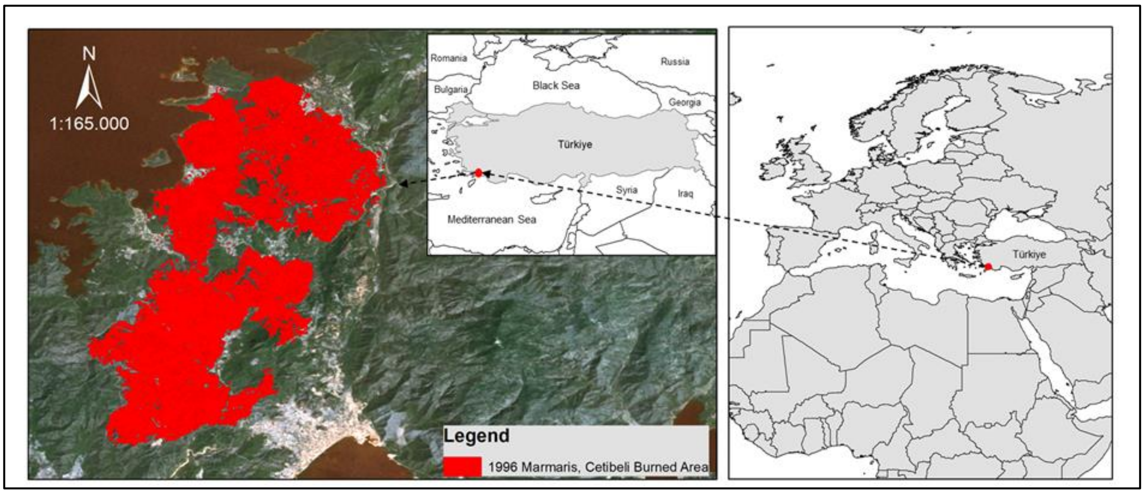

Figure 4. The Study area of Çetibeli fire in Marmaris-Muğla, Türkiye.

In the district where the Mediterranean climate prevails, summers are quite hot and dry, while winters are relatively warm and rainy. Marmaris is one of the regions that receives the most precipitation in Türkiye after Rize province, and the annual precipitation is over 1200 mm. Due to heavy precipitation in the winter months, floods and floods can occasionally occur in the district. Thunderstorms (lightning and thunder) are seen quite frequently during the passage of frontal systems in the winter. The period between May and September does not see much precipitation and is quite dry. Due to the mild effect of the sea, frost is rarely seen in the winter months. Snowfall is seen on the high mountain slopes, but it rarely falls on the coastal areas. The area is mainly covered with Turkish red pine (*Pinus brutia* Ten.), which is the dominant vegetation species of the Mediterranean Region. Detailed information regarding vegetation cover is shown below in Figure 5.

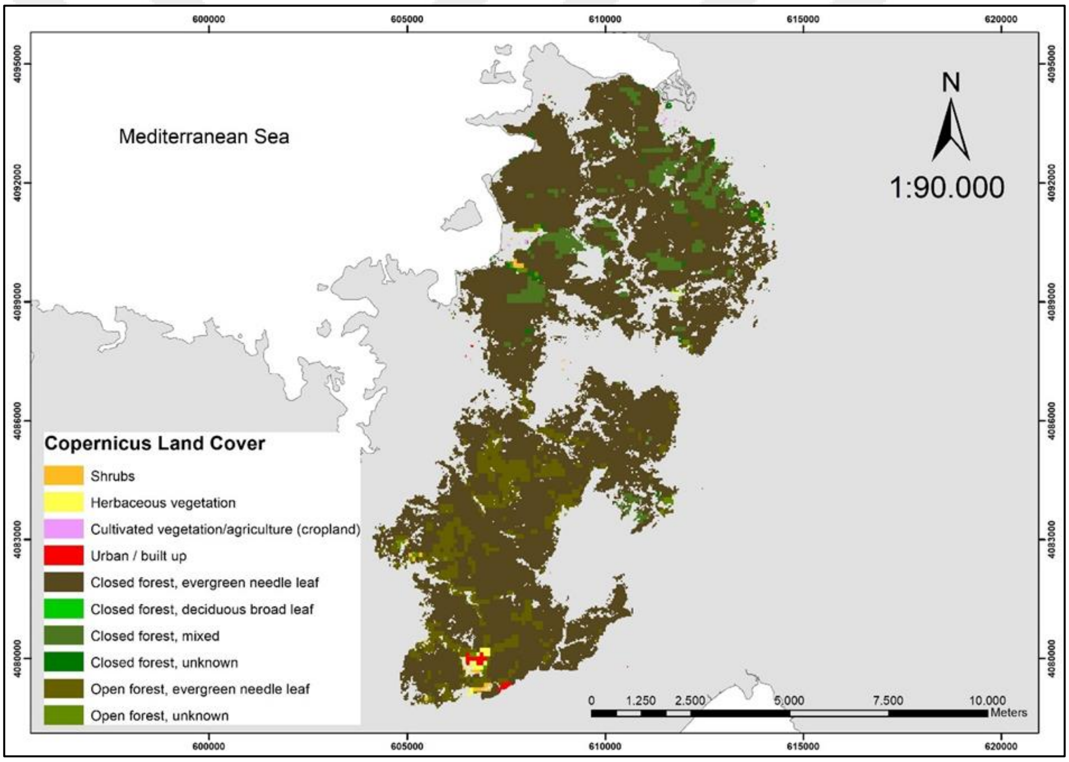

Figure 5. Land cover classification map of Çetibeli fire (2009)

Table 2 is showing vegetation cover percentage. The data again is retrieved from Copernicus. This table gives a clear picture of the composition of the current landscape by classifying the different types of land cover in the Çetibeli region following the fire. Each type of land cover is shown as a percentage of the entire study area and its area in hectares.

Table 2. Land cover percentage of Çetibeli (2019)

Copernicus Land Cover	Area (Ha)	Area (%)
Shrubs	20.3	0.3
Herbaceous vegetation	17.3	0.3
Cultivated vegetation/agriculture (cropland)	3.7	0.1
Urban / built up	16.0	0.3
Closed forest, evergreen needle leaf	5169.3	82.6
Closed forest, deciduous broad leaf	0.3	0.0
Closed forest, mixed	356.8	5.7
Closed forest, unknown	35.5	0.6
Open forest, evergreen needle leaf	595.9	9.5
Open forest, unknown	44.5	0.7

2.1.4. Marmaris – Çetibeli Fire in 1996, Türkiye

On July 27, 1996, a major wildfire occurred in the Marmaris region of Türkiye, known as the Çetibeli fire. This event had significant ecological and environmental effects. Over the course of its five days, the fire quickly spread throughout the area, affecting an estimated 6,300 hectares in total. The reason of this fire was negligence and carelessness. Figure 6 presents burned area in Çetibeli fire with Landsat 4-5 Thematic Mapper (TM) satellite images false color methodology.

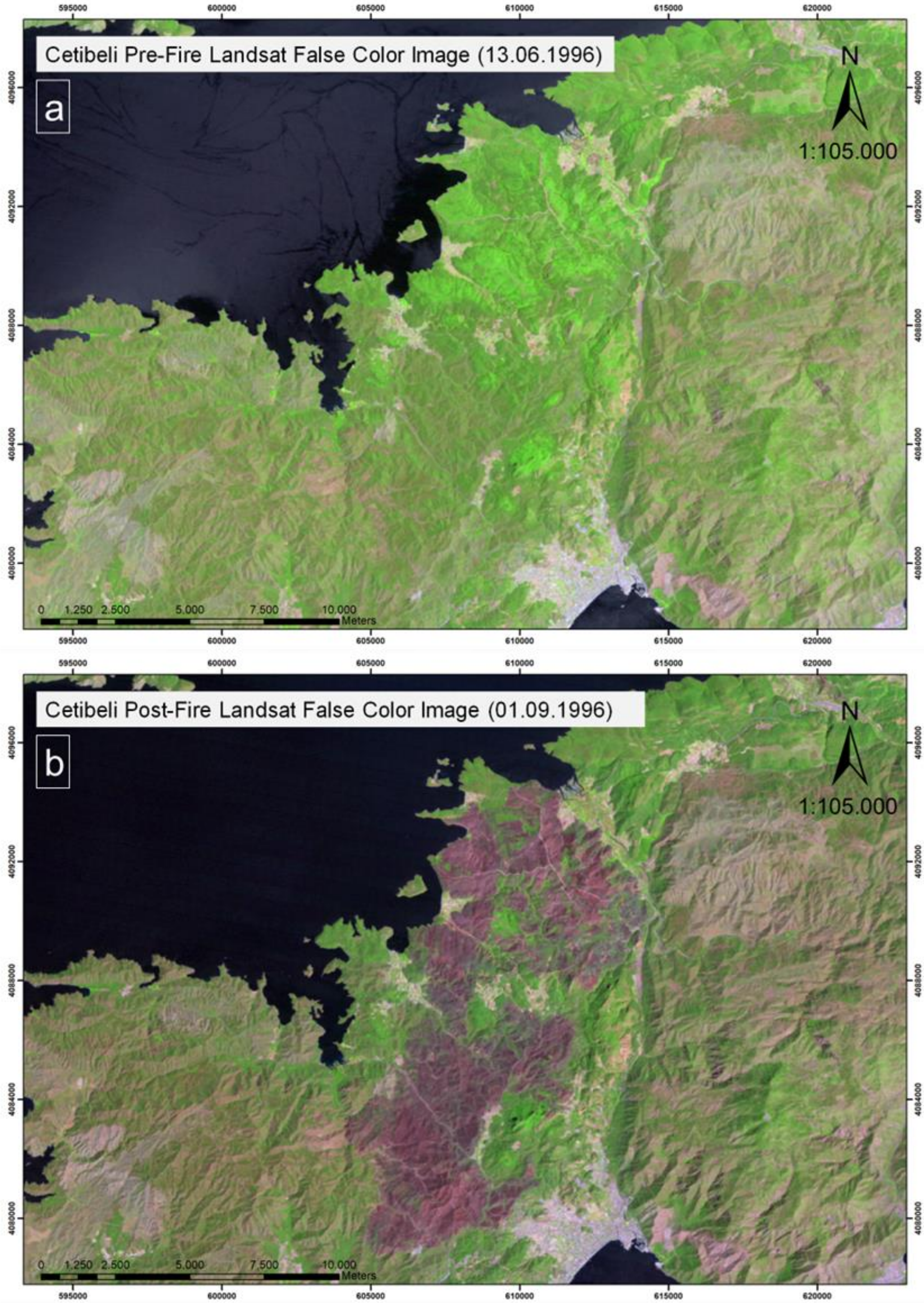

Figure 6. Çetibeli False Colour image (a: pre-fire image (13.06.1996), b: post-fire (01.09.1996)

2.2. Data Sources Preprocessing of Satellite Images

2.2.1. Remote Sensing Data

The Earth Explorer website of the United States Geological Survey (USGS) provided the remote sensing satellite data used in this analysis. More specifically, pre- and post-fire conditions were evaluated using satellite imagery from Landsat missions. Landsat 4-5 Thematic Mapper (TM) imagery was used for the years up to 2011, and Landsat 8-9 Operational Land Imager (OLI) data was used for the years 2013 through 2023 (USGS, 2024). In this study Landsat 7 images were not used because in 2003, the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) scan line corrector (SLC) failed on May 31, 2003, causing the scanning pattern to exhibit wedge-shaped scan-to-scan gaps. Burned areas were determined using Landsat 4-5 satellite images. Therefore, these images were used until 2013 for consistency.

The clarity and resolution of the analyses were improved by selecting images with the least amount of cloud cover first, in order to guarantee high-quality and dependable results. The satellite images were chosen based on whether or not they could be used to calculate the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI). As a result, only the spectral bands that were needed for these indices were downloaded. This methodical approach guaranteed that the data were optimized for the intended analyses and also relevant.

2.2.2. Data Exclusion

During this long-term study, some years were excluded from NDVI calculations due to constraints and data availability issues. Additionally, some years had incomplete or unavailable satellite data, preventing accurate calculations. Satellite malfunctions, corrupted data, and a lack of appropriate coverage all contributed to these gaps. In some cases, the available data did not meet the necessary standards for analysis. Cloud cover, atmospheric interference, and sensor anomalies all contributed to the years being excluded in order to ensure the results' reliability. For Çetibeli case, only 2012 data is excluded. But in case of Moratalla fire, following years are excluded due to the reasons explained above: 2002, 2003, 2012.

2.2.3. Data Acquisition Dates

Below in Table 3, dates of satellite images are shown for Moratalla case.

Table 3. Dates of satellite images for Moratalla fire.

Satellite	**Satellite data date**	**Year**
Landsat 4-5 TM	13/06/1994	1994
Landsat 4-5 TM	31/07/1994	1994
Landsat 4-5 TM	18/07/1995	1995
Landsat 4-5 TM	14/07/1996	1996
Landsat 4-5 TM	07/07/1997	1997
Landsat 4-5 TM	10/07/1998	1998
Landsat 4-5 TM	29/07/1999	1999
Landsat 4-5 TM	15/07/2000	2000
Landsat 4-5 TM	18/07/2001	2001
Landsat 4-5 TM	26/07/2004	2004
Landsat 4-5 TM	29/07/2005	2005
Landsat 4-5 TM	16/07/2006	2006
Landsat 4-5 TM	03/07/2007	2007
Landsat 4-5 TM	02/05/2008	2008
Landsat 4-5 TM	24/07/2009	2009
Landsat 4-5 TM	27/07/2010	2010
Landsat 4-5 TM	28/06/2011	2011
Landsat 8-9 OLI	19/07/2013	2013
Landsat 8-9 OLI	22/07/2014	2014
Landsat 8-9 OLI	25/07/2015	2015
Landsat 8-9 OLI	11/07/2016	2016
Landsat 8-9 OLI	30/07/2017	2017
Landsat 8-9 OLI	17/07/2018	2018
Landsat 8-9 OLI	20/07/2019	2019
Landsat 8-9 OLI	06/07/2020	2020
Landsat 8-9 OLI	26/08/2021	2021
Landsat 8-9 OLI	20/07/2022	2022
Landsat 8-9 OLI	31/07/2023	2023

Table 4 presents the dates of satellite images for Çetibeli case.

Table 4. Dates of satellite images for Çetibeli fire.

Satellite	Satellite data date	Year
Landsat 4-5 TM	07/15/1996	1996
Landsat 4-5 TM	07/31/1996	1996
Landsat 4-5 TM	18/07/1997	1997
Landsat 4-5 TM	21/07/1998	1998
Landsat 4-5 TM	09/08/1999	1999
Landsat 4-5 TM	11/08/2000	2000
Landsat 4-5 TM	29/07/2001	2001
Landsat 4-5 TM	16/07/2002	2002
Landsat 4-5 TM	04/08/2003	2003
Landsat 4-5 TM	21/07/2004	2004
Landsat 4-5 TM	24/07/2005	2005
Landsat 4-5 TM	27/07/2006	2006
Landsat 4-5 TM	18/05/2007	2007
Landsat 4-5 TM	01/08/2008	2008
Landsat 4-5 TM	04/08/2009	2009
Landsat 4-5 TM	06/07/2010	2010
Landsat 4-5 TM	10/08/2011	2011
Landsat 8-9 OLI	15/08/2013	2013
Landsat 8-9 OLI	17/07/2014	2014
Landsat 8-9 OLI	05/08/2015	2015
Landsat 8-9 OLI	07/08/2016	2016
Landsat 8-9 OLI	25/07/2017	2017
Landsat 8-9 OLI	13/08/2018	2018
Landsat 8-9 OLI	31/07/2019	2019
Landsat 8-9 OLI	18/08/2020	2020
Landsat 8-9 OLI	20/07/2021	2021
Landsat 8-9 OLI	16/08/2022	2022
Landsat 8-9 OLI	19/08/2023	2023

2.2.4. Climate Data

The NASA Power (Prediction of Worldwide Energy Resources) project provided the climate data, which also included temperature and precipitation totals for the past years and months. The climatic information provided by this dataset was comprehensive and reliable, which is essential for understanding how the surrounding environment impacts the research area (URL-4).

In the study following climate data are used: Mean temperature (°C) of March, April and May, annual precipitation (mm), first half year precipitation (mm) which is sum of first 6 months of year, from January to June, and growing season precipitation (mm) which is sum of months from March to August. March, April and May have been chosen in order to see the impact of spring temperatures on vegetation. First half year precipitation is chosen in relation to the timing of NDVI and NDMI measurements.

2.3. Data Processing and Calculation Steps

2.3.1. Normalized Burn Ratio (NBR)

Spectral indices created with satellite images have been used for a long time to detect burning areas. Normalized Burning Severity (NBR) is one of the most actively used indices in fire observation studies. The Normalized Burning Severity index is expressed by the mathematical equation created using near infrared and shortwave infrared bands. The NBR index is expressed in the range between [-1 and +1] (Key & Benson, 2006). The NBR for both pre-fire and post-fire conditions is calculated using the following formula (1):

$$NBR = \frac{\text{NIR+SWIR}}{\text{NIR−SWIR}} \tag{1}$$

In this equation NIR (Near-Infrared Band) is sensitive to vegetation health and biomass. While SWIR (Shortwave Infrared Band) is sensitive to changes in moisture content and is particularly effective for identifying burned areas.

2.3.2. Differenced Normalized Burn Ratio (dNBR)

In determining fire severity classes, the Differenced Normalized Burn Ratio (dNBR) method (Key & Benson, 2006), which is created by taking the difference between the pre-fire NBR index image and the post-fire NBR index image, is used (2):

$$dNBR = NBR_{\textit{pre-fire}} - NBR_{\textit{post-fire}} \quad (2)$$

This differencing method highlights changes in vegetation and soil conditions caused by fire, with higher positive values indicating more severe burn areas.

2.3.3. Classification of Fire Severity

Following the calculation of dNBR, the next step involved classifying the fire severity based on the dNBR results. The classification process converts the continuous dNBR values into discrete categories that represent different levels of fire impact. This classification is essential for interpreting and communicating the severity of the fire in a meaningful way.

Table 5. Fire severity classification (Key & Benson, 2006)

Severity level	**dNBR Range**
Unburned	dNBR < 0
Low Severity	0 ≤ dNBR < 0.1
Moderate-low Severity	0.1 ≤ dNBR < 0.27
Moderate-high Severity	0.27 ≤ dNBR < 0.44
High Severity	dNBR ≥ 0.44

After the fire severity classification, the next step involved converting the dNBR raster into vector format. This was achieved by transforming the dNBR raster into polygons using the Raster to Polygon tool in GIS. This conversion facilitated spatial analysis and allowed for more detailed examination of fire severity zones. To further analyse the relationship between fire severity and vegetation indices, the Zonal Statistics as Table tool was applied. This tool computes summary statistics of raster values within the zones defined by the input polygon features, which in this case were the fire severity classes.

The process for zonal statistics involved defining zones, each of which represented a different fire severity class, using polygons taken from the dNBR raster. This analysis used NDVI and NDMI rasters as input data for both pre- and post-fire years. The Zonal Statistics as Table tool provided important insights into the variation of vegetation health and moisture content across different fire severities by computing summary statistics, such as mean, median, and standard deviation, within each fire severity class.

The results from the zonal statistics analysis were tabulated, enabling a detailed examination of the NDVI and NDMI values according to the classified fire severity zones. This analysis helped in understanding the impact of fire on vegetation and moisture dynamics, and how these factors correlate with the severity of the burn. All analyses were performed using ArcGIS software (ESRI, ArcGIS 10.2).

2.3.4. Calculation of NDVI Values

To assess vegetation health and recovery over the long term, the Normalized Difference Vegetation Index (NDVI) values were calculated for pre-fire and post-fire years, extending up to 2023. NDVI satellite images are actively used in forest greening observation studies. The Normalized Difference Vegetation Index is produced using near infrared band images and red band images.

NDVI is expressed in the range ranging from [-1 to +1]. The NDVI images produced have high pixel values in places where plants are dense; It is expected to have low pixel values in places where vegetation is sparse. NDVI is a widely used index for monitoring vegetation vigor and biomass, calculated using the following formula (Rouse et al., 1973) (3):

$$NDVI = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \tag{3}$$

Where, RED = the red portion of the electromagnetic spectrum (0.6-0.7 μm) and NIR= the near infrared portion of the electromagnetic spectrum (0.75-1.5 μm). In Landsat 4-7, NIR is band 4, while RED is band 5. In case of Landsat 8-9, NIR is band number 5, and RED is number 4.

2.3.5. Calculation of NDMI Values

The NDMI is designed to highlight moisture differences in vegetation. It is similar to the Normalized Difference Vegetation Index (NDVI), which is used to measure vegetation health, but NDMI is more sensitive to water content in vegetation. Higher NDMI values typically indicate healthier, well-watered vegetation, while lower NDMI values suggest drier, more stressed vegetation. NDMI can be calculated using the formula below((Wilson & Sader, 2002) (4):

$$NDMI = \frac{\text{NIR}-\text{SWIR}}{\text{NIR}+\text{SWIR}} \tag{4}$$

NIR (Near-Infrared Band) is reflectance value in the near-infrared spectrum. This band is sensitive to the internal structure of healthy vegetation, which reflects more NIR light. SWIR (Short-Wave Infrared Band) is reflectance value in the short-wave infrared spectrum. This band is sensitive to moisture content in leaves. Drier vegetation reflects more SWIR light. In Landsat 4-7, NIR is band 4, while SWIR is band 5. But in Landsat 8-9, NIR is band number 5, SWIR is band number 6.

2.4 Statistical Analysis

Pearson correlation analysis was performed to investigate potential relationships between vegetation indexes (NDVI and NDMI) and climate factors such as precipitation and temperature. All statistical analyses were performed using the statistical software SPSS, Version 26.0 (SPSS 2019).

3. RESULTS

3.1. The results of the 1994 Moratalla Fire in Spain

The fire severity classification for the Moratalla region can be seen on the following map, which was created using the dNBR analysis of the 1994 fire event (Figure 7). The map is categorized into two groups according to the differenced Normalized Burn Ratio (dNBR) values: low severity (yellow) and moderate-low severity (orange). The extent and intensity of the fire-affected areas within the study region have been clarified as a result to this visual representation.

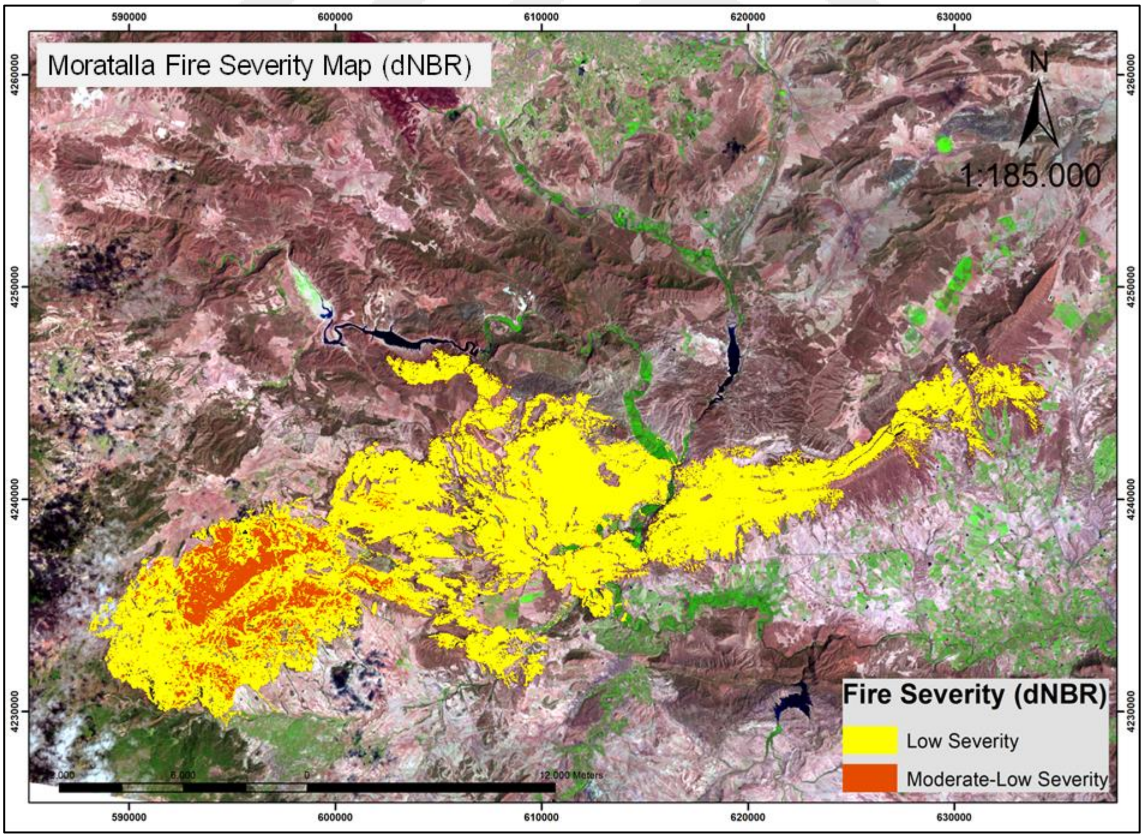

Figure 7. Fire severity (dNBR) map of Moratalla fire.

According to the land cover map, forest cover is concentrated in the western part of the Moratalla region. Similarly, the areas classified as having moderate-low fire severity are concentrated in the western region. This spatial correlation indicates that forested areas were more affected by moderate-low fire severity, implying a possible link between land cover type and fire severity. Below burned area data based on fire severity class of Moratalla region is presented. (Table 6).

Table 6. Burned Area and Percentage of Each Fire Severity Class in Moratalla, Spain.

Severity class	**Burned area (ha)**	**Percentage of Total Burned Area (%)**
Low	19.964.1	89.2
Moderate-low	2.415.1	10.8
Total	22.379.2	100

According to dNBR analysis, the total burned area in the Moratalla region is 22.379,2 hectares. The low severity class accounts for 19.964,1 hectares, or 89.2% of the total burned area. The moderate-low severity class includes 2.415,1 hectares or 8% of the total burned area.

3.1.1. Moratalla fire NDVI and NDMI Results

The analysis of Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI) values over different fire severity classes in the Moratalla region reveals significant insights into vegetation recovery post-fire. The long-term study, encompassing data from 1994 to 2023 with some exception, provides a detailed view of how vegetation health and moisture content responded to varying levels of fire severity. Below all the values have been shown in the table 7. The trend of NDVI values was given in figure 8.

Table 7. Long – term NDVI and NDMI values of Moratalla fire

Year	NDVI (LS)	NDVI (MLS)	NDVI Mean	NDMI (LS)	NDMI (MLS)	NDMI Mean
1994(Pre-fire)	0.129	0.189	0.159	-0.050	0.045	-0.003
1994(Post – fire)	0.051	0.036	0.043	-0.137	-0.142	-0.139
1995	0.078	0.084	0.081	-0.112	-0.112	-0.112
1996	0.097	0.131	0.114	-0.076	-0.047	-0.061
1997	0.125	0.166	0.146	-0.064	-0.021	-0.042
1998	0.117	0.157	0.137	-0.062	-0.017	-0.039
1999	0.107	0.148	0.127	-0.074	-0.029	-0.051
2000	0.101	0.136	0.119	-0.080	-0.044	-0.062
2001	0.119	0.168	0.144	-0.067	-0.008	-0.037
2004	0.135	0.188	0.162	-0.053	0.019	-0.017
2005	0.112	0.165	0.138	-0.066	0.002	-0.032
2006	0.125	0.172	0.149	-0.067	-0.005	-0.036
2007	0.137	0.197	0.167	-0.054	0.023	-0.015
2008	0.115	0.162	0.138	-0.070	-0.012	-0.041
2009	0.131	0.187	0.159	-0.055	0.014	-0.020
2010	0.136	0.193	0.164	-0.066	0.003	-0.031
2011	0.133	0.194	0.164	-0.055	0.023	-0.016
2013	0.167	0.233	0.200	-0.037	0.043	0.003
2014	0.157	0.219	0.188	-0.049	0.020	-0.014
2015	0.160	0.228	0.194	-0.037	0.035	-0.001
2016	0.158	0.217	0.188	-0.038	0.030	-0.004
2017	0.164	0.228	0.196	-0.032	0.050	0.009
2018	0.159	0.222	0.190	-0.033	0.046	0.006
2019	0.152	0.208	0.180	-0.019	0.053	0.017
2020	0.183	0.251	0.217	-0.015	0.074	0.030
2021	0.185	0.245	0.215	-0.001	0.088	0.044
2022	0.183	0.250	0.217	-0.006	0.085	0.040
2023	0.184	0.247	0.216	-0.014	0.078	0.032

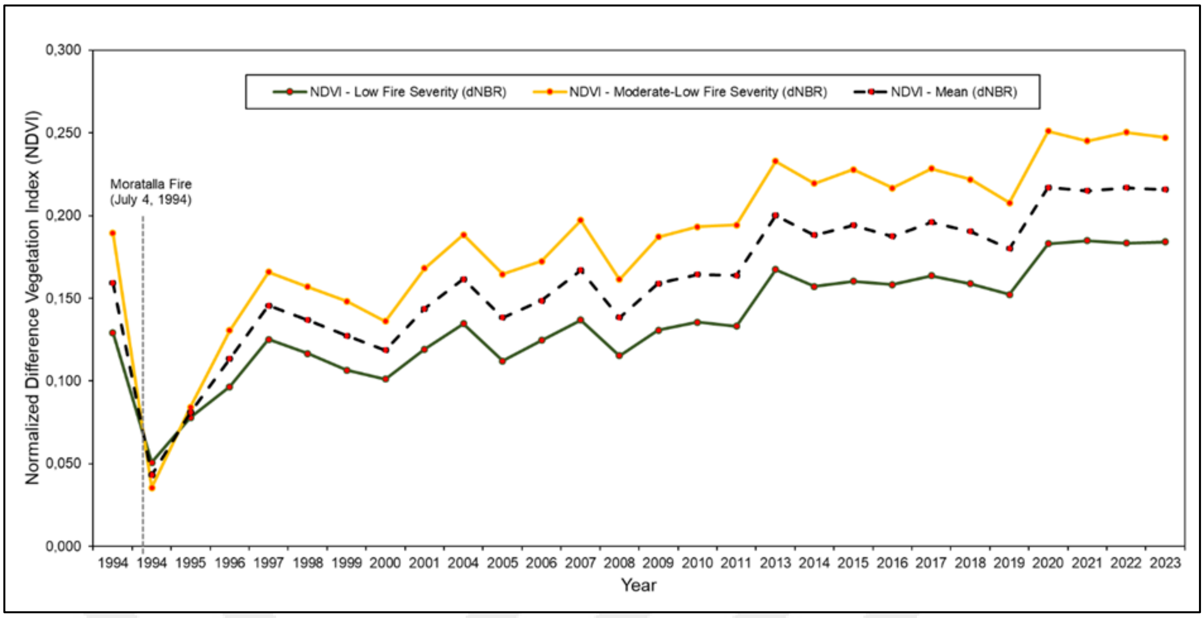

Figure 8. NDVI trends of Moratalla fire.

Based on the results, the pre-fire NDVI values for both low fire severity and moderate-low fire severity classes decreased dramatically after fire, 0.129 and 0.189, respectively. This means vegetation loss. After fire NDVI values, as well as the mean NDVI, continued to increase, except for some years (especially 2005 and 2008).

Although the low fire severity class exceeded its pre-fire value of 0.135 in 2004, it decreased again by 2 times in the next 5 years. However, after 2008 there was no significant decrease and NDVI values continued to increase, reaching the highest level after the 2021 fire: 0.185. It is interesting that this result is 1.4 times higher than the pre-fire value. This shows us that the vegetation is recovering well enough.

While the pre-fire values for moderate - low fire severity class were 0.189, this value drops to 0.036 according to the satellite images taken 3 weeks after the fire. This indicator is less than low severity class post fire, which reveals the severity of the fire. Starting in 1995, values increased, and the process continued with very little change until 1999. The decline in 2000 shows itself in this class as well: it falls from 0.148 to 0.136 with only 1 year difference. Although it increased again in the following years, it experienced its next sharp decline in 2005. So, while the values of 2004 were 0.188, in 2005 this number decreased to 0.165. If the pre-fire value is compared with the general trend, it can be said that this class reached its pre-fire value in 2004, with 0.188. After 2009, it continued to increase, leaving behind the pre-fire value. Between 1994 and 2023, the highest value observed in 2020, with 0.250. It should be noted that this value is 1,328 times higher than the value before the fire. In other words, the fire caused the formation of the area with a better regrouped, denser and healthier vegetation in both classes about 25 years later.

Mean NDVI also showed the same trend as the other 2 classes. Pre-fire value is 0.159 and after fire it decreased to 0.043. It is interesting that here pre - fire value is obtained in 2004: 0.162. Although there was a decrease later in 2005, the overall increase continues and values exceed 0.21 starting from 2020 and this trend continues until 2023, the last year of analysis. To visualise and show recovery better, map created using pre, post and 2023 NDVI raster files. Figure 9 shows vegetation recovery in Moratalla based on NDVI values. High NDVI values (closer to 1) are represented by green, indicating dense and healthy vegetation across most of the area. Oppositely, lower NDVI values (closer to -1) suggest a loss of vegetation. NDMI values also showed more or less same trend. Trend analysis was shown in figure 10.

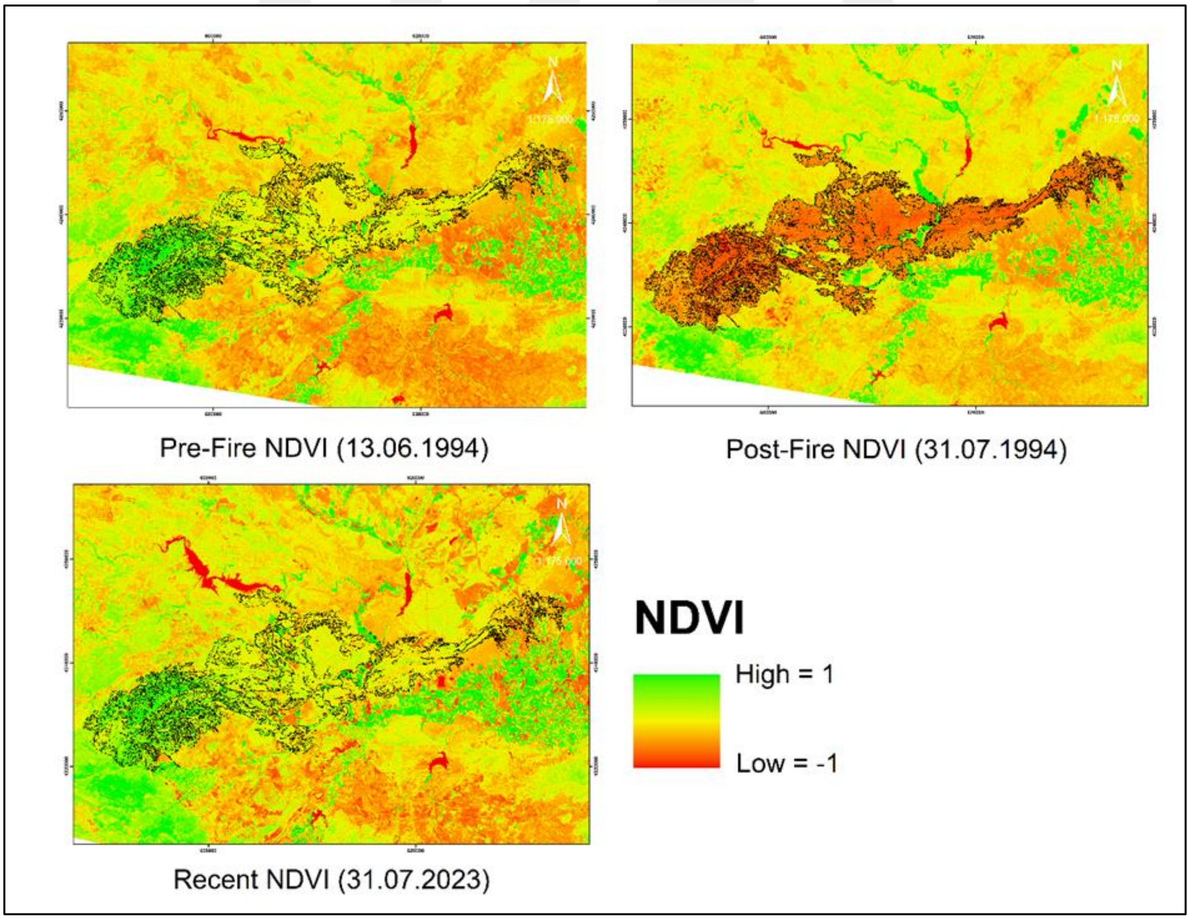

Figure 9. NDVI maps of Moratalla fire

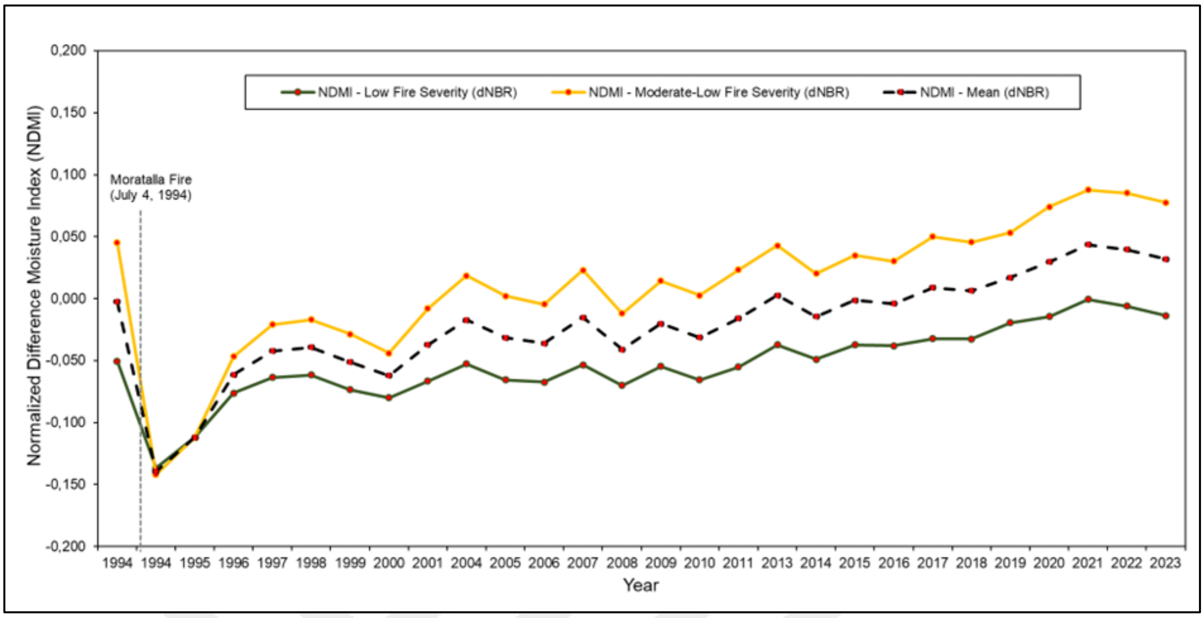

Figure 10. NDMI trends of Moratalla fire

The NDMI values for areas with low fire severity initially decreased dramatically after the fire, reaching their lowest point in 1994 to -0.137. Nonetheless, a discernible rebound emerged by 1996, despite minor variations in the index during the ensuing years. The recovery was gradual, with the NDMI values showing steady improvement over time. By around 2020, the NDMI values for low severity areas nearly returned to their pre-fire levels, reflecting a long-term recovery. The trend from 2020 onwards indicates a stabilization, with minor fluctuations but generally maintaining levels close to those before the fire. In that category negative NDMI value is dominant during that period.

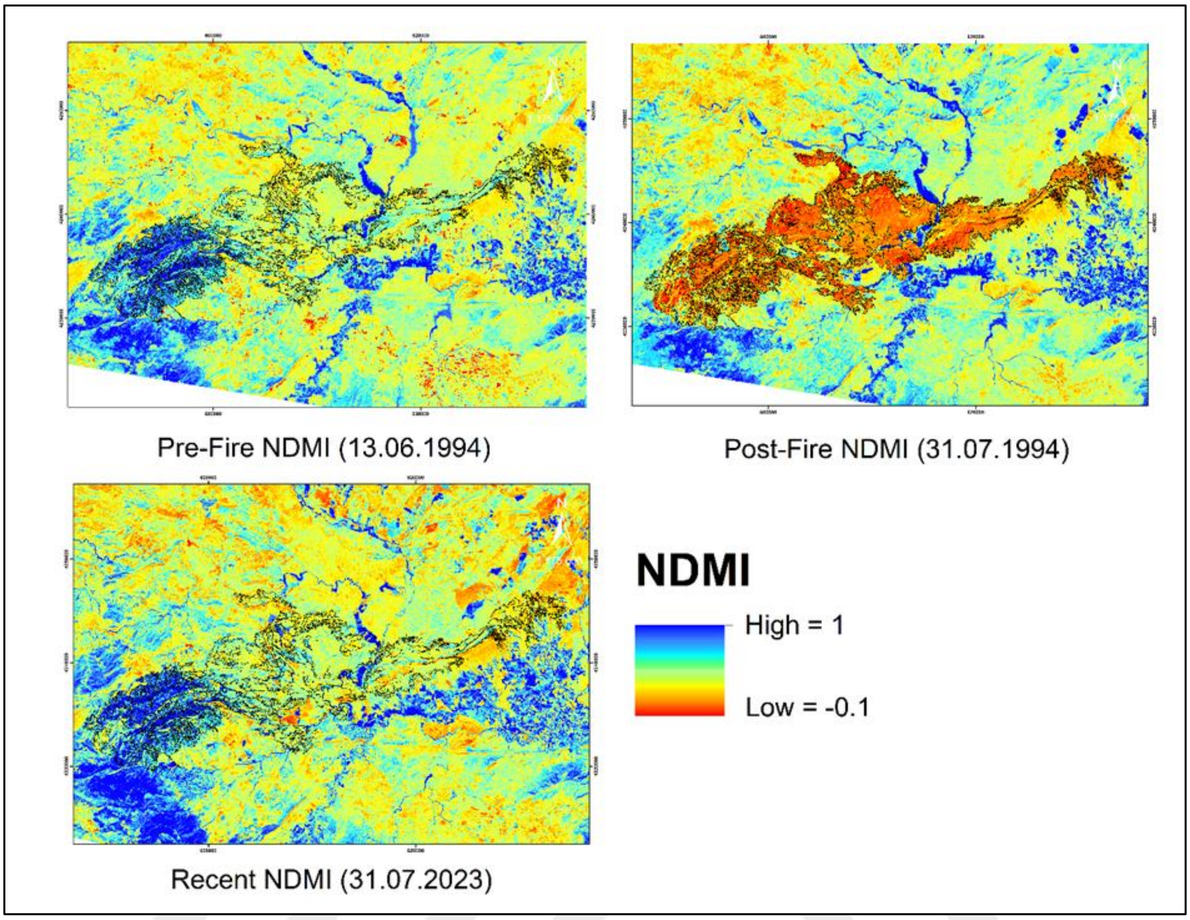

Figure 11. NDMI maps of Moratalla fire

In the moderate-low fire severity areas, NDMI values showed a sharper decline immediately after the fire, similar to the low severity areas. However, the recovery process was faster and more pronounced. By 1997, the NDMI values had already surpassed the recovery seen in low severity areas. Over the years, the NDMI continued to improve, with a few ups and downs. By 2013, the values in this class not only recovered but also exceeded pre-fire levels, indicating a stronger resilience and better moisture retention in the post-fire years. This upward trend remained consistent until 2021, when NDMI values peaked, showing a robust long-term recovery.

The same procedure has been done with NDMI values to visualise long term vegetation recovery. Figure 11 is presenting Moratalla fire NDMI maps. These lower NDMI values (closer to -0.1) reflect the loss of moisture likely due to the fire's consumption of vegetation and the subsequent drying of the soil. The areas with higher moisture content (blue) are now much less prevalent, showing the extensive impact of the fire on the region's moisture levels.

3.2. The Results of the 1996 Çetibeli Fire in Türkiye

In figure 12, second study area, Çetibeli fire burn severity map has been visualised.

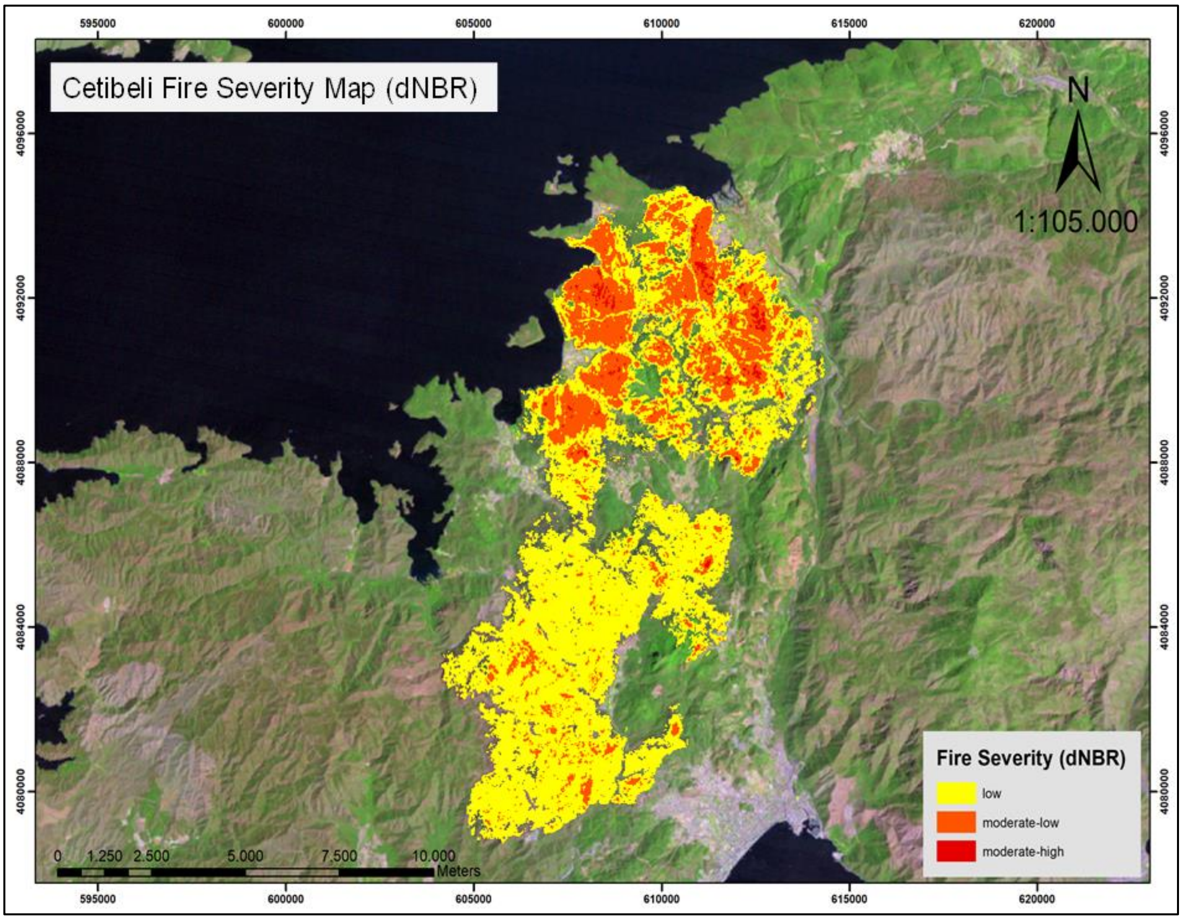

Figure 12. Fire Severity (dNBR) map of Çetibeli fire.

This map illustrates the spatial distribution of fire severity in the Çetibeli region following the 1996 fire event. After classification based on dNBR values, 3 severity classes are identified: low, moderate-low, and moderate-high. As seen in the map, moderate-high severity happened in the north part of the study area.

To complement the visual representation of the fire severity in Çetibeli, presented in Figure 12, a quantitative assessment of the burned areas is provided in Table 8. This table details the extent of each fire severity class in hectares and its corresponding percentage of the total burned area.

Table 8. Burned Area and Percentage of Each Fire Severity Class in Çetibeli, Türkiye

Severity class	**Burned area (ha)**	**Percentage of Total Burned Area (%)**
Low	4.660,9	74.5
Moderate-low	1.528,5	24.4
Moderate-high	70,2	1.1
Total	6.259,6	100

The Çetibeli region's total burned area is 6.259,6 hectares. 4.660,9 hectares, or the majority of the burned area, are classified as low severity. This class makes up 74.5% of the entire burned area, suggesting that a sizable portion of the affected area by the fire only sustained minor damage. 24.4% of the total burned area, or 1.528,5 hectares, are included in the moderate-low severity class. This suggests that there has been some noticeable damage to the vegetation, albeit not as much as in the highest severity class. 70.2 hectares, or 1.1% of the entire burned area, are classified as having moderate-high severity. This low percentage suggests that substantial vegetation damage only occurred in a small portion of the area.

Before going to NDVI and NDMI graphs, it is worth to check those values between 1996 – 2023. All the values, including mean of them have been demonstrated in table 9.

Table 9. Long – term NDVI and NDMI results of Çetibeli fire

Year	NDVI* (LS)	NDVI (MLS)	NDVI (MHS)	NDVI Mean	NDMI (LS)	NDMI (MLS)	NDMI (MHS)	NDMI Mean
1996	0.203	0.256	0.316	0.258	0.092	0.151	0.205	0.150
1996	0.078	0.046	0.035	0.053	-0.016	-0.053	-0.079	-0.049
1997	0.113	0.135	0.164	0.137	-0.051	-0.046	-0.031	-0.043
1998	0.136	0.180	0.219	0.178	-0.006	0.030	0.063	0.029
1999	0.147	0.197	0.236	0.193	0.003	0.047	0.085	0.045
2000	0.144	0.186	0.217	0.182	0.016	0.056	0.086	0.053
2001	0.148	0.178	0.200	0.175	0.010	0.033	0.053	0.032
2002	0.171	0.205	0.230	0.202	0.034	0.065	0.088	0.062
2003	0.163	0.202	0.235	0.200	0.028	0.065	0.098	0.064
2004	0.170	0.212	0.246	0.209	0.026	0.067	0.104	0.066
2005	0.167	0.212	0.244	0.208	0.024	0.067	0.100	0.064
2006	0.153	0.200	0.236	0.196	0.018	0.067	0.107	0.064
2007	0.152	0.194	0.224	0.190	0.019	0.061	0.095	0.058
2008	0.175	0.229	0.267	0.224	0.033	0.089	0.127	0.083
2009	0.178	0.231	0.266	0.225	0.042	0.094	0.131	0.089
2010	0.187	0.237	0.270	0.231	0.039	0.088	0.123	0.083
2011	0.193	0.253	0.296	0.247	0.051	0.109	0.154	0.105
2013	0.226	0.293	0.339	0.286	0.070	0.136	0.184	0.130
2014	0.236	0.309	0.359	0.301	0.080	0.153	0.204	0.146
2015	0.231	0.301	0.350	0.294	0.079	0.148	0.198	0.142
2016	0.235	0.302	0.352	0.296	0.084	0.151	0.199	0.145
2017	0.232	0.306	0.357	0.298	0.082	0.157	0.208	0.149
2018	0.239	0.313	0.366	0.306	0.088	0.161	0.213	0.154
2019	0.255	0.333	0.384	0.324	0.102	0.178	0.231	0.170
2020	0.244	0.323	0.380	0.316	0.099	0.178	0.236	0.171
2021	0.242	0.313	0.368	0.308	0.091	0.161	0.215	0.156
2022	0.233	0.314	0.367	0.305	0.089	0.168	0.221	0.159
2023	0.237	0.309	0.361	0.303	0.092	0.162	0.214	0.156

*LS: Low Severity, MLS: Moderate-Low Severity and MHS: Moderate High Severtiy according to dNBR.

The NDVI trend of all fire severity classes was given in Figure 13.

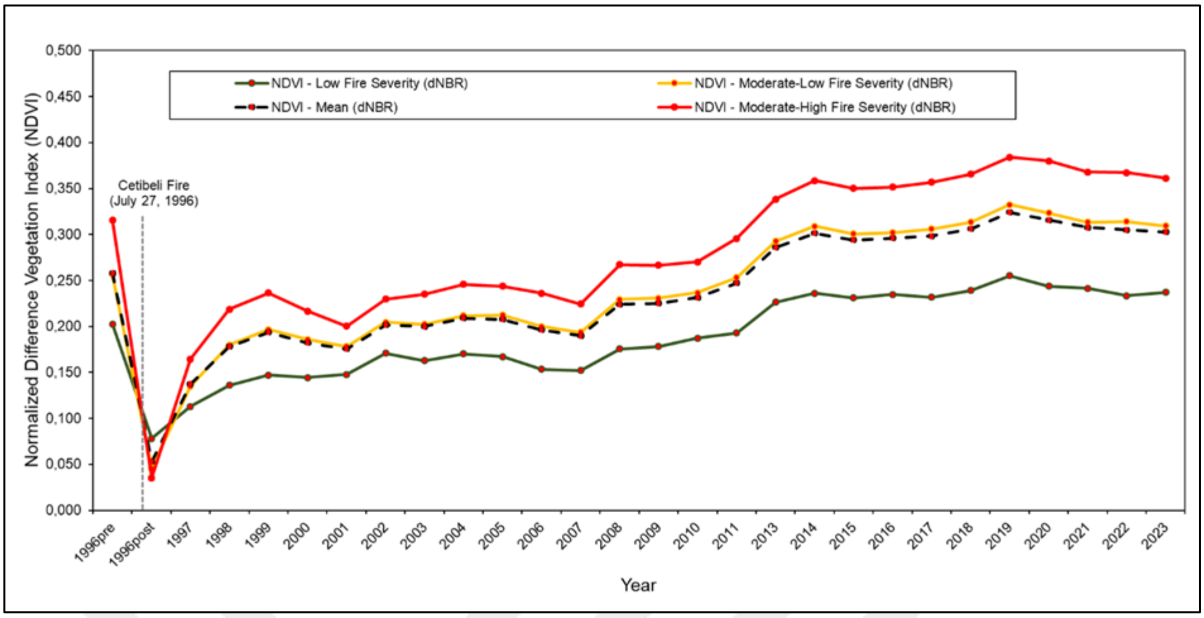

Figure 13. NDVI trends of Çetibeli fire

In all severity classes, a general trend of recovery is evident. The sharp decline post-fire was followed by a slow but steady recovery starting in 1996. The mean values demonstrated a more balanced recovery compared to individual severity classes, reflecting the varying degrees of fire impact. Mean NDVI is reached its pre – fire values by 2013.

Pre fire value for low fire severity class is 0.203. However, after the fire, it sharply decreased to 0.078. In the following years, the NDVI values continue with an increasing trend. This increase even reached 0.171 in 2002. But in the following years, especially in 2003, 2006 and 2007, decreases were observed. Since 2008, the NDVI values have been increasing again, reaching their highest value of 0.255 in 2019. This category reached their pre-fire NDVI value of 0.226 in 2013. It should even be noted that this number is higher than the pre-fire value

Pre fire value for moderate low fire severity class is more than low fire severity class, in other words 0.256. However, after the fire, there was a decrease here too, and the values fall to 0.046. NDVI, which was 0.135 in 1997, suddenly increased to 0.180 just 1 year later. Although this growth experienced a slight decrease in 2001, the general trend continues. Already in 2002, the NDVI value exceeds 0.20. This category reached its pre-fire value of 0.253 in 2013. Since 2014, the increase continued and even exceeded 0.30. Moderate- low fire severity class shows its highest value in 2019 with 0.333

There is a clear pattern of recovery over time in the NDVI for areas with moderate-high fire severity. The NDVI was comparatively low (0.035) immediately following the 1996 fire, indicating significant damage to the vegetation. The NDVI grew over the ensuing years, hitting 0.217 by the year 2000. This suggests that following the initial impact, vegetation started to gradually recover. The NDVI showed a usually upward trend within 2001 and 2006, with small variations that stabilized at about 0.244 by 2005. The NDVI values have been steadily improving since 2007, reaching notable values in 2013 (0.339) and 2018 (0.366). This may indicate that the vegetation in these regions has recovered to a more developed stage. Moderate high fire category reaches its pre fire value by 2013. The recovery trajectory of the mean NDVI, which is an average of all fire severity classes, is comparable. In 1996, the NDVI dropped to 0.053 following the fire.

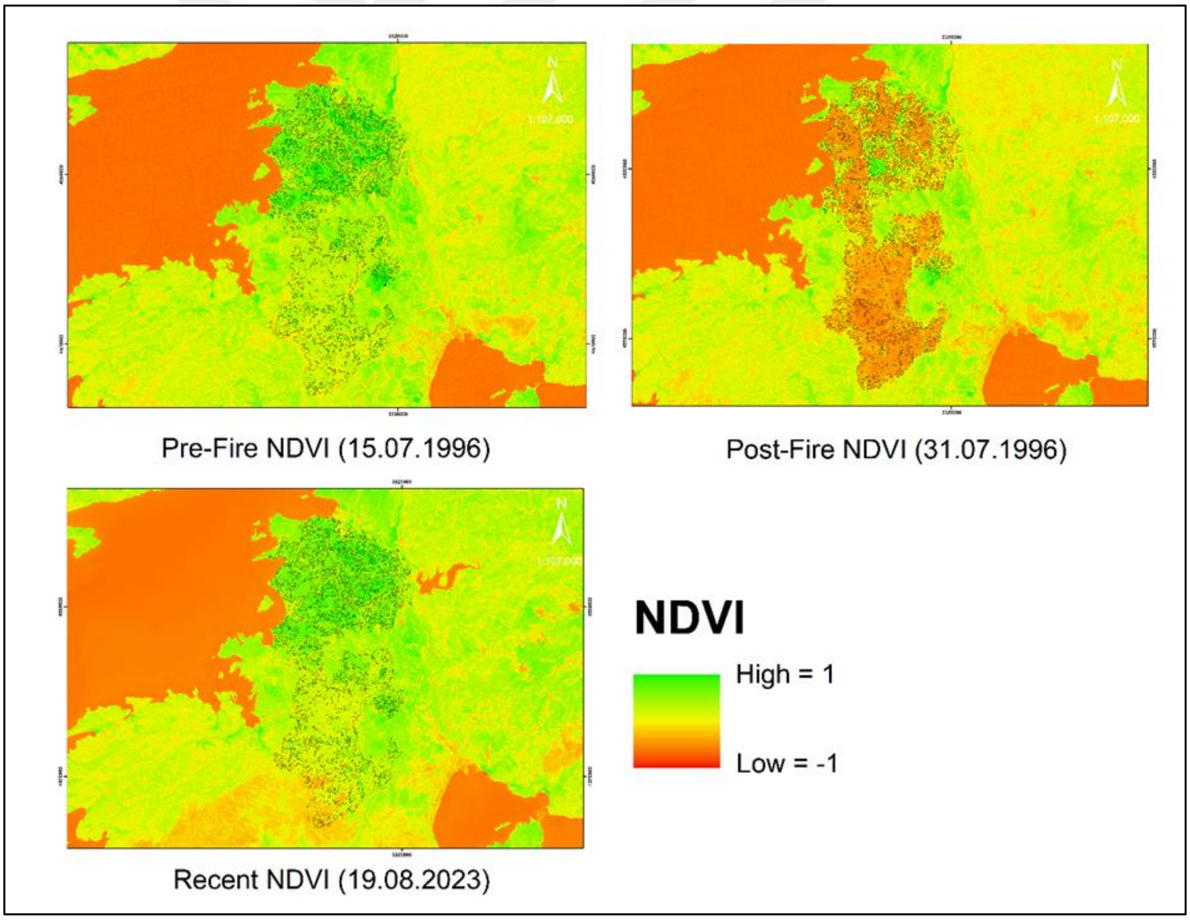

Figure 14. NDVI maps of Çetibeli fire

The mean NDVI rose gradually over the ensuing years, peaking at 0.175 by 2000, indicating a general improvement in the vegetation throughout the research area. The mean NDVI improved over the next few years, although more slowly than in the areas with moderate-to-high fire severity. It reached at 0.224 in 2017 and continued to recover steadily in the years that followed. Mean NDVI has reached pre – fire level by 2013. After trend analysis, visual map of NDVI values is shown in Figure 14. Despite initial low NDVI values after fire, in a long term clear vegetation recovery can be observed in Çetibeli region. Trend analysis of NDMI values have been demonstrated in figure 15.

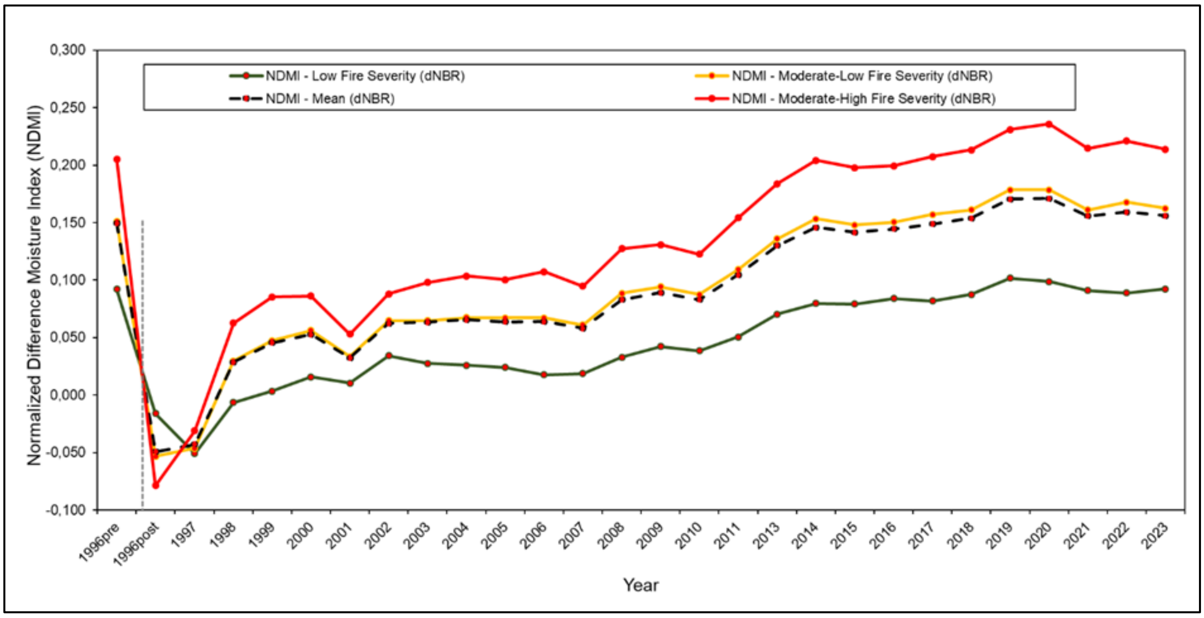

Figure 15. NDMI trend analysis of Çetibeli fire

After the 1996, the NDMI values rapidly decreased for each category, reaching negative values by the next year. This sudden drop demonstrates the direct effect on the moisture content of the vegetation. But soon after, there was a quick recovery, and by 1998, NDMI values were positive once more except for low fire severity class. The NDMI values improved steadily over the ensuing years, from 2000 to 2010, suggesting a steady restoration of vegetation moisture levels. During this period, some fluctuations have been observed, especially between 2004 – 2008. The NDMI values for areas with low fire severity stabilized by 2023, indicating that the moisture content of the vegetation had successfully recovered and was close to pre-fire levels. But this category has exceeded its pre – fire values in 2019 with 0.102

In these areas with moderate – low fire, the recovery was more gradual; by 1998, NDMI values had started to rise. Over the course of the 2000s, the recovery trend persisted, with NDMI values consistently improving. In areas with moderate-to-low fire severity, by 2014, the NDMI values had stabilized at levels indicating a healthy moisture content, and they had returned to positive values, indicating that the vegetation had fully recovered. The pre – fire level also reached in the same year – 2014. After 2017, NDMI values constantly are beyond pre - fire level.

In spite of this harsh initial effect, the NDMI values started to rise in 1998 and beyond. A consistent rise in NDMI was observed during the recovery in areas with moderate-high severity, especially starting in 2003 as the vegetation's moisture content progressively increased. The NDMI values had reached pre-fire levels by 2017, indicating a significant recovery in the moisture content of the vegetation in these areas. NDMI visualising of Çetibeli fire is shown in figure 16. Clear recovery can be observed according to pre - fire, post - fire and last NDMI maps.

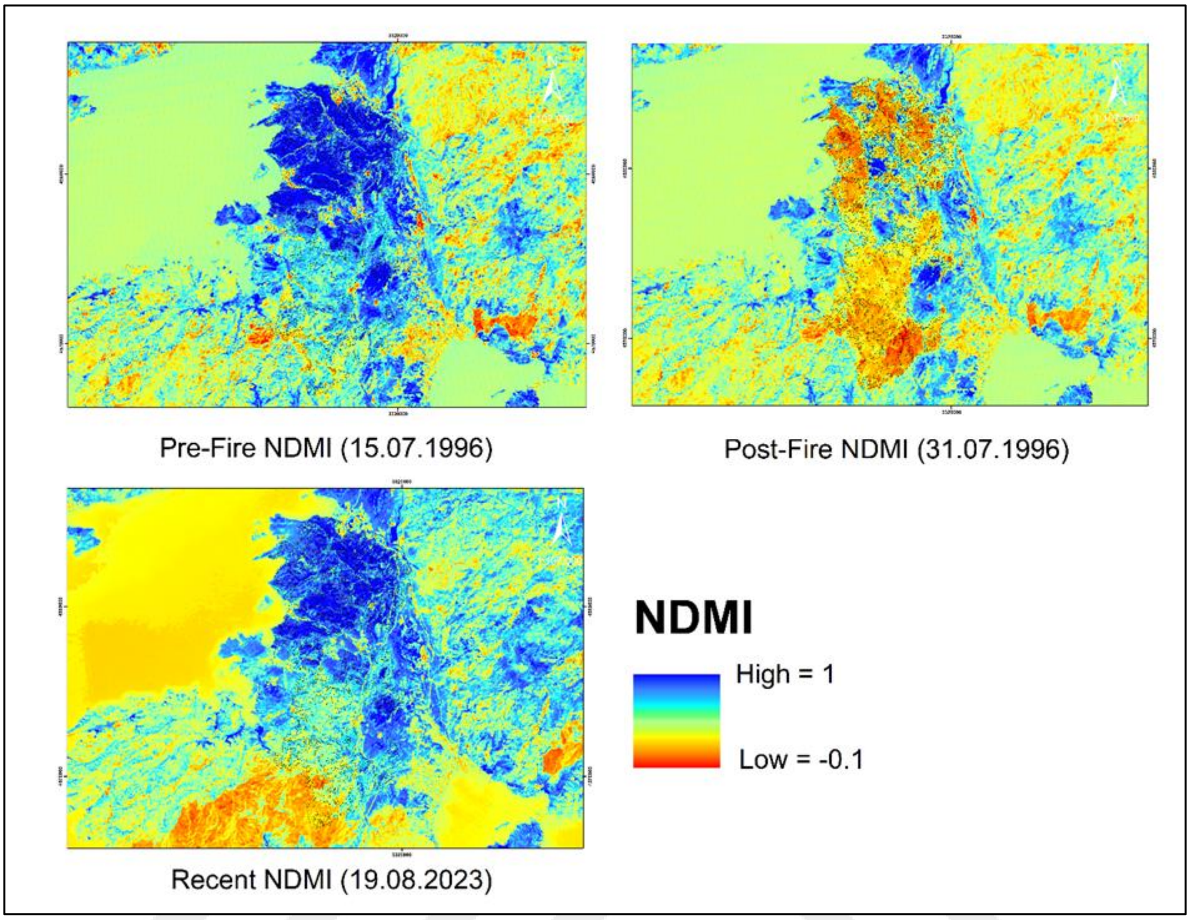

Figure 16. NDMI maps of Çetibeli fire

3.3. The Results of Correlation Analysis Between Post Fire Vegetation Recovery and Climatic Factors

The results indicated that NDVI low, moderate, and mean values are strongly correlated with NDMI low, moderate, and mean values, with correlations ranging from 0.936 to 0.998 (p=0.01) in Moratalla fire. This suggests a strong relationship between vegetation health across different levels (Table 10). First half-year precipitation (ranging r= 0.530 and 0.577 p=0.01) and annual precipitation (ranging r= 0.485 and 0.477 p=0.05) show moderate positive correlations with NDVI and NDMI (ranging r= 0.521 and 0.577 p=0.01) values, suggesting that more precipitation is associated with higher vegetation health and moisture content (Table 10).

The correlation between First half-year precipitation and NDVI moderate low is r=0.531 (p=0.01) and for NDMI low is r=0.572 (p=0.01), showing that precipitation during the first half of the year has a notable impact on both vegetation health and moisture. Growing season variable shows strong positive correlations with both NDVI and NDMI values (e.g., r=0.655 (p=0.01) with NDMI low), indicating that the growing season has a significant impact on vegetation health and moisture content (Table 10). Temperature variables generally show weaker and non-significant correlations with NDVI and NDMI compared to all precipitation variables (Table 10.)

Table 10. Correlation matrix for Moratalla fire

Variables[1]	NDVI L	NDVI ML	NDVI MEAN	NDMI L	NDMI ML	NDMI MEAN	T March	T April	T May	AN PREC	GS PREC	FHY PREC
NDVI L	1											
NDVI ML	,986**	1										
NDVI MEAN	,995**	,998**	1									
NDMI L	,952**	,936**	,946**	1								
NDMI ML	,952**	,969**	,965**	,971**	1							
NDMI MEAN	,958**	,963**	,965**	,988**	,996**	1						
T March	-,150	-,171	-,162	-,127	-,176	-,160	1					
T April	-,073	-,036	-,051	-,199	-,135	-,159	,130	1				
T May	,133	,120	,126	,159	,130	,141	,134	,172	1			
AN PREC	,485*	,470*	,477*	,543**	,521**	,533**	-,261	-,371	-,162	1		
GS PREC	,631**	,591**	,609**	,655**	,640**	,649**	-,280	-,423*	-,105	,760**	1	
FHY PREC	,560**	,531**	,545**	,572**	,574**	,577**	-,257	-,395	-,123	,771**	,951**	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

-1 0 1

[1]L = Low severity, ML = Moderate-Low severity, T= Temperature (°C), AN= Annual, GS= Growing Season, FHY = First Half Year, PREC = Precipitation (mm)

The same variables have been used in Çetibeli case. Correlation analysis was done to see climatic factors impact on vegetation recovery. Below correlation analysis of Çetibeli fire is shown with some climate variables (Table 11).

Table 11. Correlation analysis of Çetibeli fire

Variables[1]	NDVI L	NDVI ML	NDVI MH	NDVI MEAN	NDMI L	NDMI ML	NDMI MH	NDMI MEAN	T March	T April	T May	AN PREC	GS PREC	FHY PREC
NDVI L	1													
NDVI ML	,994**	1												
NDVI MH	,987**	,998**	1											
NDVI MEAN	,994**	1**	,998**	1										
NDMI L	,982**	,977**	,973**	,978**	1									
NDMI ML	,979**	,984**	,984**	,985**	,995**	1								
NDMI MH	,969**	,979**	,982**	,980**	,989**	,998**	1							
NDMI MEAN	,977**	,982**	,983**	,983**	,996**	1**	,998**	1						
T March	,174	,138	0,111	,135	,165	,121	,088	,119	1					
T April	,480*	,492*	0,486*	,488*	,414*	,425*	,416*	,419*	,331	1				
T May	,176	,157	0,161	,164	,160	,149	,148	,152	,050	,141	1			
AN PREC	,276	,234	0,214	,236	,299	,272	,257	,273	-,101	-,261	-,062	1		
GS PREC	-,012	-,021	-0,027	-,021	,064	,061	,075	,067	-,342	-,432*	-,259	,380	1	
FHY PREC	,284	,288	0,284	,286	,304	,314	,317	,313	-,337	-,156	-,107	,654**	,433*	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

-1 0 1

[1]L = Low severity, ML = Moderate-Low severity, MH= Moderate-High severity, T= Temperature (°C), AN= Annual, GS= Growing Season, FHY = First Half Year, PREC = Precipitation (mm)

Strong significant positive correlations were observed between NDVI and NDMI categories which is around 0.970 (p=0.01). Although the correlation is not significant, annual precipitation and first half year precipitation show positive correlations with NDVI and NDMI values (Table 11). This suggests that higher annual precipitation generally supports better vegetation health and moisture content, but the effect is not as strong as the temporal trends.

T March and T May show weaker and non-significant correlations with NDVI and NDMI values, indicating that temperature in March and May has a less significant impact on vegetation health and moisture. But on the other hand, T April has significant positive correlations with NDVI and NDMI values (e.g. ranging r=0.414 and r=0.492 p=0.05), suggesting that higher temperatures in April may have a more noticeable effect on vegetation and moisture content. Growing season precipitation has weak and non-significant correlations with NDVI and NDMI, which may indicate that during the growing season, other factors might be more critical for vegetation health than precipitation alone. Although the correlation is not significant, first half year shows moderate positive correlations with NDVI and NDMI, implying that winter precipitation might be more crucial for the overall health of vegetation and soil moisture leading into the growing season (Table 11).

3.4. Trend Analysis of Climate Variables

Addition to correlation analysis, graphical trend analysis of climatic variables was added to the study. Figure 17 represents 3 different precipitation patterns and their trend in Moratalla case.

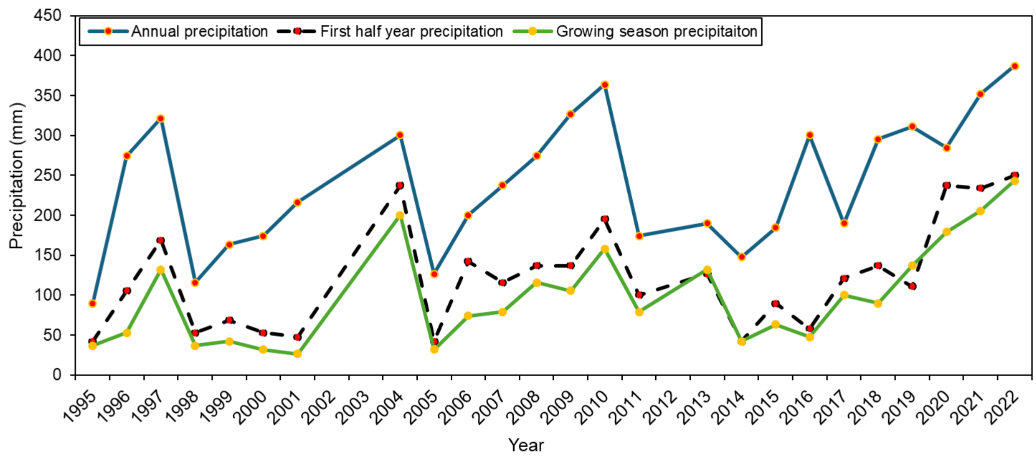

Figure 17. Precipitation pattern trend (Moratalla)

Results showed that sometimes increase in annual precipitation does not guarantee same impact growing season precipitation. This explains stronger correlation between growing season precipitation and NDVI values. The mean temperature (T) of spring months were (March, April and May) shown in figure 18.

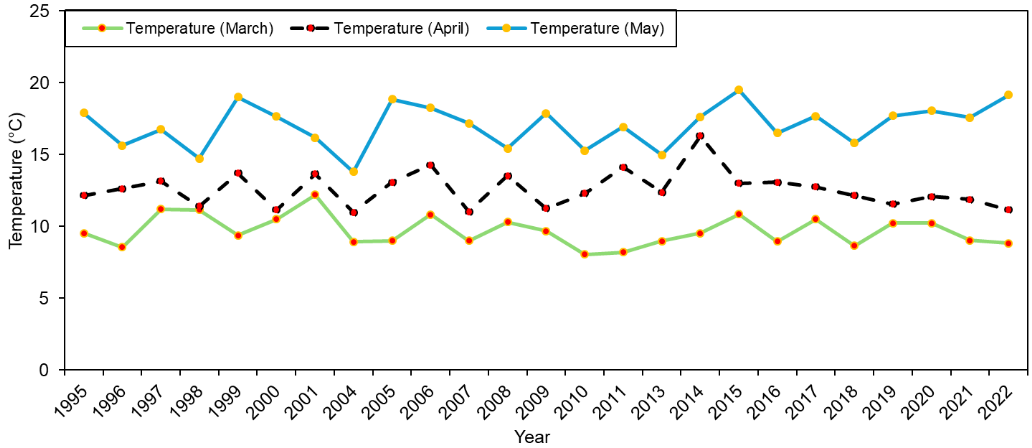

Figure 18. Mean temperature of spring months (Moratalla)

A trend line analysis of the growing season precipitation and mean NDVI values over the study period is presented in Figure 19. A positive correlation was found in the correlation analysis between these two variables, indicating a relationship between variations in growing season precipitation and NDVI values, which reflect the health of the vegetation.

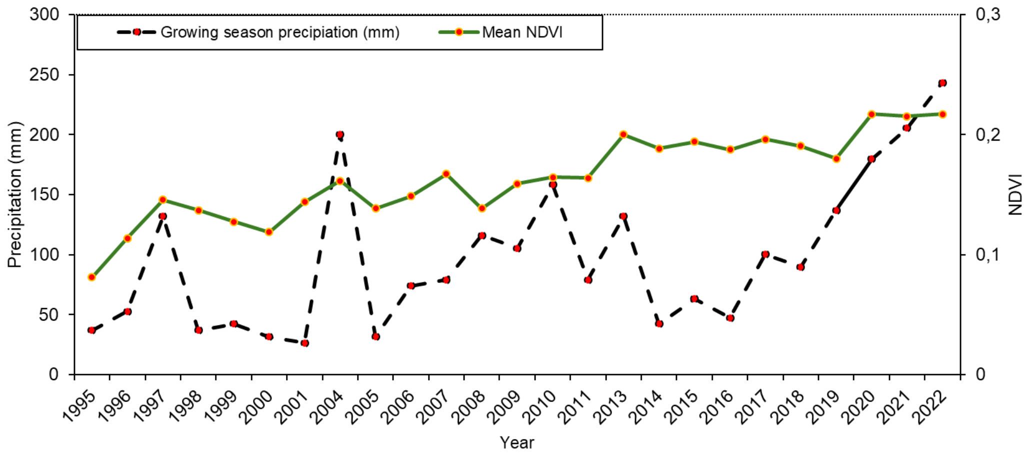

Figure 19. Trend line analysis growing season precipitation and NDVI mean (Moratalla)

Higher rainfall during the growing season encourages vegetation growth and improves vegetation cover, as shown by the trend line analysis, which shows that mean NDVI values tend to increase as growing season precipitation increases. Below figure 20 illustrates precipitation patterns trend over the years for Çetibeli fire. Trends of spring months mean temperature is shown figure 21.

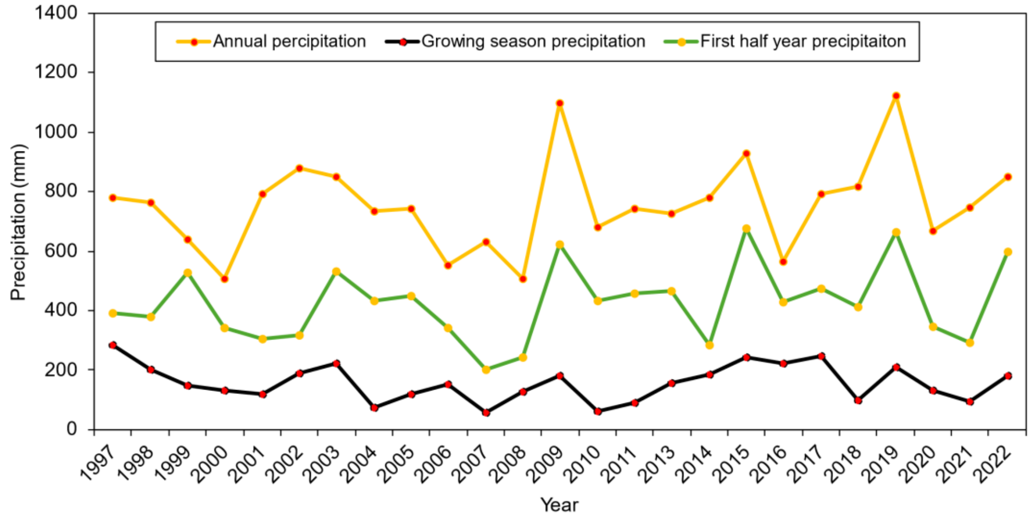

Figure 20. Precipitation patterns trends (Çetibeli)

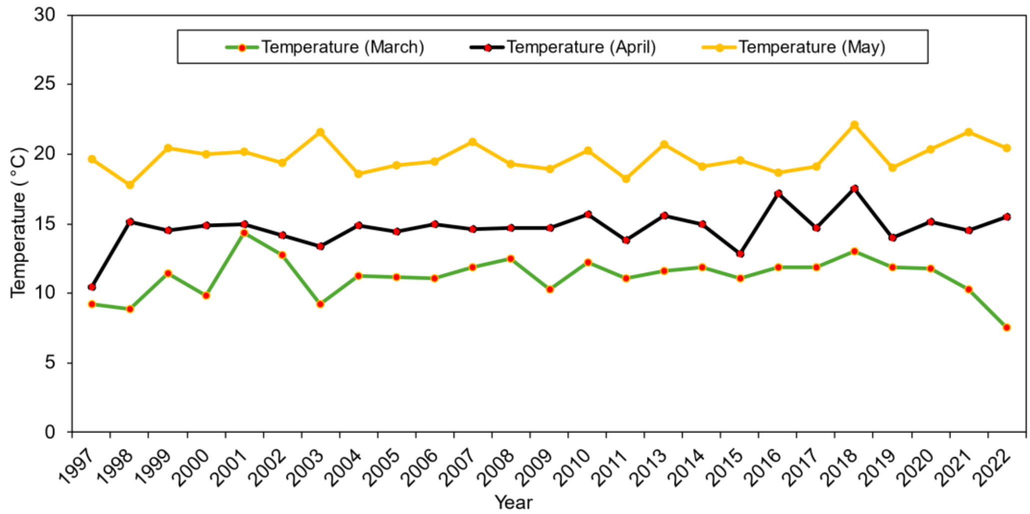

Figure 21. Mean temperature of spring months (Çetibeli)

According to the result, mean temperature already reaching out 20 degrees and above in May. Hot summers are unavoidable in this region. Figure 22 represents trend analysis April mean temperature and mean NDVI value. Figure 23 shows trends of first half year precipitation and mean NDVI values. The result showed that first half year precipitation and NDVI mean values are slightly associated with each other.

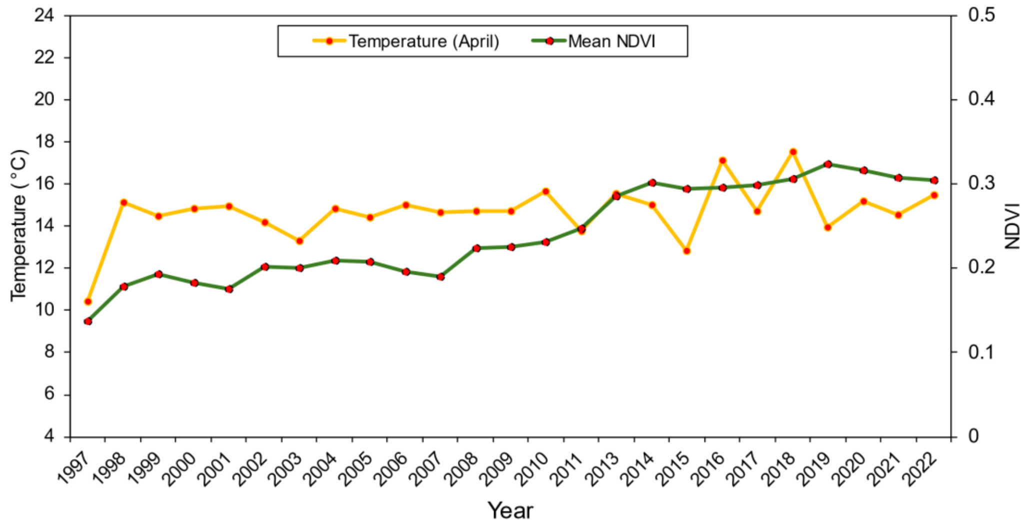

Figure 22. Trend analysis of mean April temperature and mean NDVI (Çetibeli)

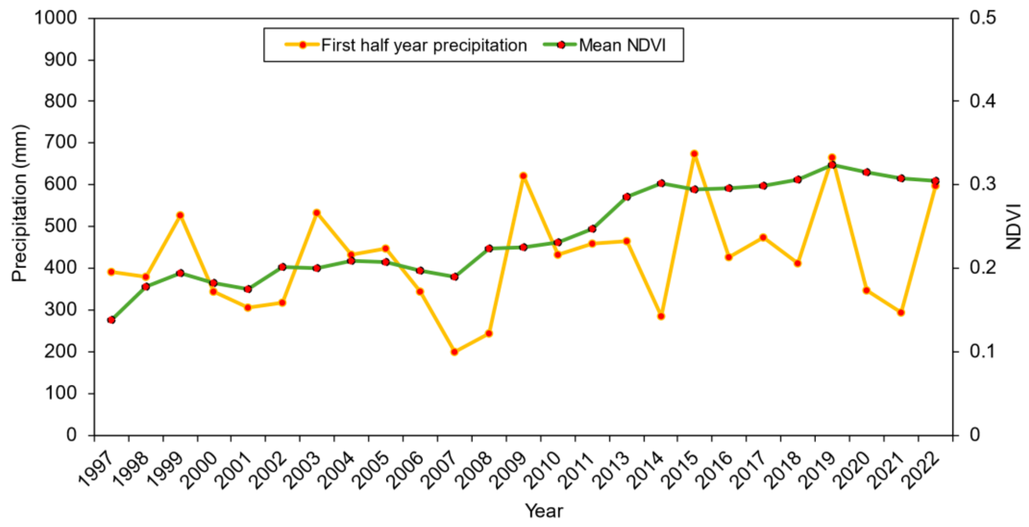

Figure 23. Trend analysis of first half year precipitation and mean NDVI (Çetibeli)

4. DISCUSSION

4.1. Fire Severity and Vegetation Recovery

Long - term post - fire analysis showed a noteworthy pattern of vegetation recovery after wildfire events in both Spain and Türkiye. The results showed that areas with higher fire severity tend to show a faster and more noticeable recovery over time (Fig. 8, 10, 13 and 15). In particular, compared to areas that experienced low fire severity, the NDVI and NDMI values in high fire severity classes (Moderate-low and Moderate - High) demonstrated a notable increase post-fire, reaching and even surpassing pre-fire levels more quickly. The datasets from both regions showed a consistent observation of this trend. These results align with previous research that has documented similar patterns of post-fire vegetation Dynamics (Bright et al., 2019; Hao et al., 2022). Positive correlation between fire severity and vegetation recovery also is found in a study in USA (Jin et al., 2012).

High-severity fires have the potential to rapidly release nutrients that have been stored in organic matter and vegetation. In the short term, this nutrient flush can greatly increase soil fertility by creating an enriched environment that fosters vigorous plant growth during the recovery stage. The establishment and growth of a diverse plant community can be facilitated by these nutrient-enriched conditions in the long run, which could account for the positive correlation in the study. Because of ash deposition, nutrient release from burned vegetation, and the creation of stable nutrient forms, the nutrient content in both the O (humus or organic) and A (topsoil) horizons frequently increases immediately following a fire. One of the most crucial elements in determining the soil's nutrient content over the long term as well as immediately following a fire is the persistence of ash deposition on the soil's surface. Understanding the composition and spatial distribution of nutrients in the soil is crucial for the restoration of burned habitats, as it may serve as a barrier to vegetation recovery (Caon et al., 2014).

Another reason for fast and total recovery is reduced competition after fire. After a fire, there is less competition, which promotes quicker vegetation recovery and colonization, especially for species that are well-suited to these circumstances. An increasingly mature and stable ecosystem results from the gradual return of resource competition as the ecosystem heals and plant biomass rises. Lower competition during the early post-fire phase, however, can lead to an explosion of growth and regeneration that aids in the ecosystem's recovery (Zwolinski, 1990).

Since it is fire – prone ecosystem, most of species, especially *Pinus* are fire adapted. Those species have different traits that allow them to germinate after fire such as serotinous cones and canopy seed banks. Their seeds are stimulated by fire, heat or smoke. They are well adapted to fire environment, and it helps them to recover faster in such an extreme situation (Pausas, 2015). When checking NDVI and NDMI values, it is clear that in both cases those values exceeded pre–fire values which can be explained by the reasons mentioned above (Fig. 8, 10, 13 and 15). In summary, these species have evolved to not only survive fires but to use them as an opportunity to regenerate and flourish, resulting in vegetation that can be denser and healthier than before the fire occurred. Another study done in Türkiye is also revealed that, *Pinus brutia* which is main species in Marmaris region has ability of fast regeneration and full recovery happens usually between 5-20 years (Tavşanoğlu & Gürkan, 2009).

Both cases showed total recovery after fire, but it took different time intervals. Moratalla fire is recovered between 2007 – 2009 depending on the severity class, which mean after 13 – 15 years. However, the analysis of post-fire vegetation recovery in Moratalla region between 1994 and 2023 revealed an unexpected pattern in pre-fire NDVI values. Specifically, mean NDVI values prior to the 1994 fire were relatively low, around 0.159, which typically indicate sparse vegetation or ecosystem stress. This raised the possibility that another fire or disturbance may have occurred shortly before 1994, contributing to these lower values. Unfortunately, no NDVI data prior to 1982 is available for analysis, as Landsat 4, the first satellite capable of capturing high-resolution NDVI data, was launched on July 16, 1982. The lack of earlier data further complicates the assessment of pre-fire vegetation conditions, as the low NDVI values could reflect recovery from a prior disturbance. Therefore, while remote sensing is effective for monitoring long-term vegetation trends, the absence of data from earlier periods limits ability to fully reconstruct the landscape’s historical context prior to the 1994 fire.

In Çetibeli region, area recovered itself in 2013, 17 years following the fire. As can be seen, recovery rate is quite close in both cases. And it is common pattern in Mediterranean basin or climate condition (McMichael, C. E., et al, 2004). In case of Moratalla, post recovery NDVI values are 1.3 – 1.4 times higher than pre – fire values. This is also result of previous fires in the area as 1990th was fire season in Spain. Recently burned area is the reason of low pre – fire values.

Forest fires are a very relevant and important issue for the Marmaris region. Research by Ahmet (2023) has shown that 2172.2 ha in the period 2000-2005, 194.1 ha in the period 2006-2010, 17.7 ha in 2011-2015, and 163.2 ha in the period 2016-2020 were burned due to forest fires. It is interesting that between 2021 and 2023, the amount of burnt area increased and reached 15.757,5 ha. Of this, 11.003,9 hectares burned in 2021 alone. In terms of general trend, since 2000, 18,259.6 ha of land has burned in Marmaris (Siyavus, 2023).

Since the results revealed that vegetation reached its pre–fire values after approximately 15-20 years, those areas are turning to fire danger zones again. Especially, it should be considered that recent fires in Marmaris happened just few years ago. On one hand, it is positive findings that vegetation recovered after severe fire, but on the other hand it puts concern about potential forest fires in this study site.

4.2. Post Fire recovery and Climate Variables

In case of Moratalla fire, analysis showed low and non-significant negative correlation between NDVI/NDMI and mean temperature of March, April (Table 10). It is an expected result for semi – arid place such as Murcia, Moratalla. Higher temperatures during these crucial months can cause the vegetation to struggle to recover by reducing soil moisture, delaying vegetation recovery, and increasing evapotranspiration.

Oppositely to Moratalla, Çetibeli analysis revealed that early spring temperature is significant moderate positive correlated with vegetation recovery (Table 11). According to Zhan et. al (2022) findings, vegetation growth is more susceptible to precipitation than to temperature in the arid and semi-arid zones, while temperature dominated vegetation dynamics in the semi-humid zone, and the sunshine duration was essential for vegetation growth in these regions.

In terms of precipitation, Moratalla fire showed strong positive correlation between growing season precipitation and NDVI/NDMI values (Table 10). It is followed by moderate positive correlation for the categories first half year and annual precipitation. Water is the most important factor that restricts the growth of vegetation in semi-arid regions like Moratalla. Because of the low yearly precipitation in these regions, the vegetation there is heavily reliant on water availability for growth. Consequently, any increase in precipitation during this time can greatly promote the growth and recovery of vegetation following a disturbance such as a fire. It shows the importance of drought on vegetation growth (Blanco-Rodríguez et al., 2023).

In Çetibeli, annual and first half year precipitation resulted with non-significant and weak positive correlation between NDVI and NDMI values (Table 11). With an annual rainfall of 800 - 1200 mm in regions like Çetibeli, water availability usually does not inhibit the growth of vegetation. In comparison to semi-arid regions where vegetation is heavily dependent on limited precipitation, more humid environments, like Çetibeli, typically provide plants with an adequate supply of water throughout the year.

Despite high amount of annual rainfall, fires are unavoidable in Marmaris region due to high mean and maximum temperature of summer months, and also very low amount of precipitation during summer, especially July and August can go without any rain at all. In this case, fuel availability increases the risk of wildfires.

5. CONCLUSION AND RECOMMENDATIONS

Analysis of the long-term post-fire recovery in Türkiye (Marmaris-Çetibeli) and Spain (Moratalla) showed that areas with higher fire severity recover more quickly and efficiently, as shown by the NDVI and NDMI values exceeding pre-fire levels in a shorter amount of time. In Marmaris region full recovery takes almost 17 years, while in Moratalla this number is 13-15 years. That slight difference is also due to pre – fire NDVI and NDMI values since in Çetibeli case this number is higher than Moratalla case.

In the Cetibeli region of Türkiye, NDVI values were calculated according to fire severity classes, revealing that areas with higher fire severity exhibited faster post-fire recovery in terms of NDVI values. While these results provide valuable insights into vegetation recovery, they also highlight the need for a more nuanced approach in future analyses. Specifically, future studies should take into account not only fire severity but also fuel types when calculating NDVI. For instance, NDVI recovery patterns may differ in low-severity fire areas dominated by species such as *Pinus brutia* compared to other vegetation types. By considering both fire severity and fuel types, future analyses could provide a more comprehensive understanding of post-fire recovery dynamics, allowing for more targeted management strategies

The divergent relationships found in Moratalla and Çetibeli between vegetation recovery and climate variables highlight how local climate conditions influence post-fire recovery trajectories. In contrast to the semi-arid region of Moratalla, where vegetation recovery is heavily dependent on precipitation, the more humid environment of Çetibeli displays a more moderate relationship between temperature and NDVI values. These results emphasize how crucial it is to take site-specific climate factors into account when managing post-fire recovery in various Mediterranean regions.

Fire regime is another important issue in this ecosystem. In the context of fire paradox, study results indicate that those areas are sensitive to another fire in coming years. Adaptive fire management strategies should be developed to balance the ecological benefits of natural fire regimes with the risks of uncontrolled wildfires, given the rapid vegetation recovery observed in areas of high fire severity. This includes mechanical thinning or controlled burns to lower fuel loads and stop the accumulation of overgrowth, which can trigger future fires that are more intense.

Remote sensing technologies have shown to be extremely useful for tracking vegetation recovery and evaluating the effects of fires. More use of remote sensing with higher spatial, temporal, and spectral resolution data to enhance the precision and efficacy of fire management strategies can be recommended. Sentinel-2, Landsat-9, and commercial satellites are examples of satellites with higher resolution imagery that can provide more precise information on soil conditions, moisture content, and vegetation structure. This information can be used for early detection of fire risks and post-fire recovery dynamics. Lower-resolution imagery may miss smaller or more dispersed fire-affected areas, making it more difficult to identify and monitor them. This is another benefit of integrating high-resolution data.

Comprehensive, real-time monitoring capabilities can be achieved by combining higher-resolution satellite data with other remote sensing instruments, such as drones and ground-based sensors. As a result, it will be easier to evaluate fire risks and handle post-fire recovery.

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RESUME

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His first year was in University of Lisbon, Institute Superior De Agronomia (ISA). For his specialization, he chose forest fires and moved to University of Lleida (UDL), Spain. Finally, he has decided to end up his MEDfOR program in Türkiye by writing my thesis in Trabzon. Karadeniz Technical University (KTU) is the only partner university that offers multiple options regarding usage of GIS and Remote Sensing.