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Evaluating Wildfires Risk in Tlemcen, Algeria:

The Role of Climate Change, Vegetation Health, and Drought Patterns

Master of Climate Change Engineering

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APPROVAL PAGE

Dedication

I dedicate this thesis to my family—my parents who have been my foundation, my sisters who have been my constant support, and my wife whose love and encouragement have sustained me throughout this journey.

To my mentors, whose wisdom and guidance have shaped my academic path and inspired my pursuit of knowledge.

To the province of Tlemcen, whose magnificent landscapes and ecological richness have been both my subject of study and source of inspiration.

And to Algeria, my beloved homeland, whose natural heritage I hope to help preserve for generations to come.

Statement of the Author

I, the undersigned, hereby declare that this thesis entitled "Evaluating Wildfires Risk in Tlemcen, Algeria: The Role of Climate Change, Vegetation Health, and Drought Patterns" is entirely my own work. All sources used have been properly acknowledged and cited according to academic standards. I confirm that the ideas, analyses, and conclusions presented are original except where explicitly stated otherwise.

I further declare that this thesis has not been submitted, either in whole or in part, to any other institution for the award of a degree, diploma, or certificate.

This thesis is submitted in fulfillment of the requirements for the Master's Degree in Climate Change Engineering from the Pan African University of Water and Energy Sciences including Climate Change.

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Biographical Sketch

I was born in Maghnia, Tlemcen in 1999 and graduated from Dkhessi Mohammed High School. I pursued my higher education at the University of Tlemcen, where I earned a Bachelor's degree in Forestry (2017-2020) and a Master's degree in Forest Management (2020-2022).

During my time at the University of Tlemcen, I was an active member of the Scientific and Cultural Club of Forestry. At the Pan African University of Water and Energy Sciences including Climate Change (PAUWES), I served as the leader of the multimedia team within the Community of Practice (CoP). In this role, I collaborated with a diverse team to organize multiple events and created media materials that contributed to their success, including the "Life at PAUWES" video that was projected during the graduation ceremony of the 8th cohort.

My team, Afrivix, achieved semifinalist status at the Geneva Challenge, demonstrating our commitment to addressing global issues through innovative solutions.

I have completed three valuable internships that have enriched my academic and professional experience. The first was a collaboration between PAUWES and the University of Gulich, focused on GIS applications with QGIS. The second was a practical internship at the National Park of Tlemcen, studying forest fires in the region. The third was an academic internship at the University of Minho in Portugal, where I worked with GIS and remote sensing experts and participated in multiple field trips to various forest types throughout Portugal.

My interdisciplinary background, which combines technical expertise in environmental monitoring with practical field experience and collaborative project management, has given me a broad range of skills that enable me to approach complex ecological challenges with both rigorous scientific thinking and effective communication strategies. These varied experiences have given me a broad range of skills that span forestry science, forest fire management, geographic information systems, remote sensing, climate analysis, multimedia production, and team leadership. This unique combination of skills has prepared me to conduct meaningful research on climate-vegetation-fire relationships in Mediterranean ecosystems while effectively communicating findings to a variety of stakeholders.

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Finally, I wish to thank my family for their unwavering support, patience, and encouragement throughout my studies.

Abbreviations and Acronyms

NDVI - Normalized Difference Vegetation Index

EVI - Enhanced Vegetation Index

GIS - Geographic Information System

MODIS - Moderate Resolution Imaging Spectroradiometer

LST - Land Surface Temperature

CHIRPS - Climate Hazards Group InfraRed Precipitation with Station data

FireCCI - Fire Climate Change Initiative

ESA - European Space Agency

GEE - Google Earth Engine

CSV - Comma-Separated Values

LULC - Land Use and Land Cover

IGBP - International Geosphere-Biosphere Programme

NIR - Near-Infrared

QA - Quality Assurance

DGF - Directorate General of Forests (Direction Générale des Forêts)

C.F.T. - Conservation of Forests of Tlemcen

EFFIS - European Forest Fire Information System

SPEI - Standardized Precipitation Evapotranspiration Index

IPCC - Intergovernmental Panel on Climate Change

A.S.A.L. - Algerian Space Agency (Agence Spatiale Algérienne)

WUI - Wildland-Urban Interface

MCD12Q1 - MODIS Land Cover Type Product

MOD13Q1 - MODIS Vegetation Indices Product

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Abstract

This study investigated the complex interactions between climate patterns, vegetation dynamics, and wildfire activity in Tlemcen Province, Algeria over the period 2000-2019. Using an integrated approach combining remote sensing, Geographic Information Systems (GIS), and statistical analysis, the research quantified both directional trends and changing variability in key environmental parameters. Time series data from MODIS vegetation indices (NDVI and EVI), CHIRPS precipitation measurements, MODIS land surface temperature, and FireCCI burned area products were analyzed across four 5-year periods to identify significant relationships. Results revealed that climate variability, rather than directional climate change, emerged as the dominant driver of ecosystem dynamics, with widening interquartile ranges in both precipitation and temperature indicating increased environmental extremes. Vegetation health showed moderate positive correlation with precipitation (Pearson's $r = 0.60$) and moderate negative correlation with temperature ($r = -0.67$). Both fire frequency and burned area exhibited strong negative correlations with vegetation indices ($r = -0.78$), suggesting that in this Mediterranean semi-arid context, healthier vegetation with higher moisture content reduced fire susceptibility. Contrary to expectations, fire activity decreased substantially over the study period despite conditions theoretically favorable for increased fire occurrence. Land cover analysis identified significant transitions from forest (net loss of 23,000 hectares) to shrubland (net gain of 47,000 hectares), representing a shift toward more xeric landscape structure with implications for ecosystem services and fire regimes. These findings highlight the importance of considering variability patterns alongside directional trends and multiple interacting factors when assessing Mediterranean ecosystem responses to environmental change.

Key words

Mediterranean ecosystems, Remote sensing, Wildfire dynamics, vegetation indices, Land cover change, North African ecology.

1. INTRODUCTION

Mediterranean ecosystems represent one of the world's most vulnerable biomes to climate change and anthropogenic pressures, with increasing temperatures, altered precipitation patterns, and changing disturbance regimes threatening their ecological stability (Giorgi & Lionello, 2008). The interplay between climate variables, vegetation dynamics, and wildfire activity forms a complex feedback system that shapes landscape evolution and ecosystem services in these semi-arid regions (Pausas & Fernández-Muñoz, 2012). In North Africa, particularly in Algeria, these environmental interactions remain understudied despite their critical importance for ecological management and climate adaptation planning (Slimani et al., 2014). This research focuses on Tlemcen Province in northwestern Algeria, a region characterized by Mediterranean climate conditions and diverse vegetation communities, making it an ideal setting to investigate climate-vegetation-fire relationships in a changing environment.

The Mediterranean Basin has experienced significant warming over recent decades, with temperature increases often exceeding global averages (Lionello & Scarascia, 2018). While overall precipitation trends show a general decrease across the region, they exhibit greater spatial and temporal heterogeneity than temperature patterns (Vicente-Serrano et al., 2014). In Algeria, climate observations reveal complex regional variations, with northwestern areas experiencing different trends than central and eastern regions (Meddi et al., 2010). These climate shifts directly influence vegetation health and productivity, which in turn affect wildfire regimes in a cascading ecological response (Gouveia et al., 2017). Understanding these interactions requires integrated approaches that combine multiple environmental indicators and analytical techniques.

Vegetation dynamics in Mediterranean landscapes respond to both climatic drivers and disturbance events, creating feedback mechanisms that shape ecosystem trajectories. Remote sensing techniques have proven valuable for quantifying these vegetation responses through indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), which capture different aspects of plant health and structure (Alcaraz-Segura et al., 2009). Studies across other Mediterranean regions have demonstrated correlations between precipitation patterns and vegetation greenness, with water availability generally acting as the primary limiting factor for plant growth (Vicente-Serrano et al., 2013). However, these relationships can vary significantly based on vegetation type, topography, and soil characteristics, necessitating region-specific analyses (Gouveia et al., 2016).

Fire represents a fundamental ecological process in Mediterranean ecosystems, with natural and anthropogenic ignitions interacting with climate and vegetation to determine fire frequency, intensity, and extent (Pausas et al., 2008). While warming temperatures and increased drought conditions generally promote fire activity, landscape-level factors such as fuel load,

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connectivity, and moisture content often modulate this relationship (Turco et al., 2016). Recent research has identified complex patterns in Mediterranean fire regimes, with some regions exhibiting unexpected trends that contradict simple climate-fire models (Turco et al., 2013). In Algeria specifically, wildfire dynamics have received limited scientific attention despite their ecological and socioeconomic importance, creating a significant knowledge gap regarding the factors controlling fire regimes in North African Mediterranean contexts (Meddour-Sahar et al., 2013).

Land cover transformations, particularly the conversion between forest and shrubland communities, represent another critical dimension of Mediterranean landscape change (Acácio et al., 2017). These transitions can result from climate stress, fire disturbance, land use pressures, or their combined effects, creating complex causal networks that shape ecosystem structure and function (Moreira et al., 2011). The expansion of shrublands at the expense of forests—a pattern observed across many Mediterranean regions—has significant implications for biodiversity, carbon storage, water cycling, and fire behavior (Fernandes, 2013). Remote sensing approaches enable the quantification of these land cover changes, providing essential insights into the trajectory and pace of landscape transformation (Vilar et al., 2016).

Previous research on Mediterranean environmental dynamics has predominantly focused on European and Middle Eastern regions, with comparatively less attention given to North African contexts (Slimani et al., 2014). The few studies conducted in Algeria have typically addressed individual components of the climate-vegetation-fire system rather than their integrated relationships (Meddour-Sahar et al., 2013; Slimani et al., 2014). This geographical and methodological imbalance limits our understanding of whether patterns observed in northern Mediterranean regions apply to North African ecosystems, which may exhibit distinct environmental responses due to their different bioclimatic conditions and land use histories (Médail & Quétel, 2003). As climate change accelerates, this knowledge gap hampers the development of effective adaptation and management strategies for vulnerable North African landscapes.

The absence of integrated approaches represents a significant limitation in current understanding. Most studies examine either climate-vegetation relationships or fire-vegetation interactions in isolation, neglecting the complex feedbacks between these components (Batllori et al., 2013). Additionally, research often focuses on directional trends in environmental variables without adequate consideration of changing variability patterns, which may have greater ecological significance than shifts in mean conditions (Giorgi et al., 2004). Finally, the reliance on coarse temporal and spatial scales in many regional analyses can mask important localized dynamics that drive landscape-level responses to environmental change (Vicente-Serrano et al., 2013).

This study addresses these research gaps through an integrated analysis of climate trends, vegetation dynamics, and wildfire activity in Tlemcen Province, Algeria over a 20-year period

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(2000-2019). By combining remote sensing, Geographic Information Systems (GIS), and statistical approaches, the research quantifies both directional trends and changing variability patterns in key environmental parameters. The study provides a comprehensive assessment of spatial and temporal interactions between climate variables (precipitation, temperature), vegetation indices (NDVI, EVI), and fire metrics (frequency, burned area) in a North African Mediterranean context, filling a critical knowledge gap in the scientific literature. The findings contribute to both ecological theory regarding Mediterranean ecosystem responses to environmental change and practical applications for land management and climate adaptation planning.

The significance of this study extends beyond its scientific contributions to addressing urgent environmental management challenges. Tlemcen Province, like many Mediterranean regions, faces increasing threats from climate change, land degradation, and altered disturbance regimes, with potentially severe consequences for ecosystem services and human livelihoods (Slimani et al., 2014). By enhancing understanding of climate-vegetation-fire relationships, this research provides evidence-based insights for developing adaptive management strategies that can enhance ecosystem resilience while mitigating risks to human communities and natural resources. The methodological approach, combining multiple remote sensing indices, climate metrics, and fire statistics, also offers a template for environmental monitoring that could be applied to other vulnerable regions facing similar challenges.

The scope of this research encompasses three major components of the Mediterranean environmental system (climate, vegetation, and fire) analyzed at both spatial and temporal dimensions. Climatically, the study examines precipitation and temperature patterns across Tlemcen Province, quantifying both mean trends and intra-period variability over two decades. For vegetation assessment, the research analyzes NDVI and EVI dynamics derived from MODIS satellite imagery, capturing different aspects of plant health and structure across diverse ecosystem types. The fire analysis incorporates both frequency and burned area metrics, enabling assessment of changing fire regimes throughout the study period. Land cover change analysis provides an additional dimension by quantifying transitions between major ecosystem types, particularly forest-to-shrubland conversion. By integrating these components, the study captures the complex interactions and feedback mechanisms operating across the landscape.

The overarching objective of this research is to enhance understanding of climate-vegetation-fire relationships in a North African Mediterranean context through integrated analysis of environmental change in Tlemcen Province, Algeria (2000-2019). Specific objectives include: (1) quantifying temporal trends and spatial patterns in precipitation, temperature, vegetation indices, and fire activity across the study area; (2) assessing statistical relationships between climate variables, vegetation health, and fire metrics to identify key drivers and interactions; (3) analyzing land cover transitions, particularly between forest and shrubland ecosystems, and their relationship with climate and fire dynamics; (4) developing a conceptual model of environmental feedbacks based on empirical findings; and (5) deriving management

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implications and adaptation recommendations based on the research outcomes. These objectives guide the methodological approach and analytical framework employed throughout the study.

The environmental interactions examined in this research have profound implications for sustainable development, conservation planning, and climate adaptation strategies. Mediterranean ecosystems provide essential services—including water regulation, carbon sequestration, biodiversity maintenance, and recreational value—that support human well-being and ecological stability (Underwood et al., 2009). As climate change accelerates and human pressures intensify, the resilience of these systems faces unprecedented challenges, necessitating improved understanding of environmental relationships to inform management decisions (Doblas-Miranda et al., 2017). By analyzing climate-vegetation-fire dynamics in Tlemcen Province, this study contributes actionable knowledge for enhancing ecosystem resilience, mitigating fire risks, and adapting to changing environmental conditions in vulnerable Mediterranean landscapes.

In addressing the research objectives, this study employs an integrated methodological approach combining remote sensing, GIS, and statistical analysis to detect and quantify environmental changes across Tlemcen Province. The research analyzes MODIS-derived vegetation indices, CHIRPS precipitation data, MODIS land surface temperature products, and FireCCI burned area datasets to characterize the relationships between climate parameters, vegetation health, and fire activity over a 20-year period. By aggregating data into four 5-year periods (2000-2004, 2005-2009, 2010-2014, 2015-2019), the analysis balances the need to reduce interannual variability with the goal of detecting meaningful temporal trends. This methodological approach enables robust assessment of both directional changes and shifting variability patterns in the climate-vegetation-fire system, providing insights into the complex environmental dynamics shaping this North African Mediterranean landscape.

This thesis is structured to present a comprehensive analysis of climate-vegetation-fire relationships in Tlemcen Province. Following this introduction, Chapter 2 provides a detailed review of relevant literature on Mediterranean environmental dynamics, remote sensing applications, and ecosystem management approaches. Chapter 3 describes the study area. Chapter 4 explains the methodological framework employed, including data sources, processing workflows, and analytical techniques. Chapter 5 presents the key findings regarding climate trends, vegetation dynamics, fire patterns, and their statistical relationships, followed by a discussion of their ecological implications and management relevance. Finally, Chapter 6 summarizes the main conclusions, acknowledges limitations, and offers recommendations for future research and environmental management. Together, these chapters address the fundamental research question: How do climate variability, vegetation dynamics, and fire activity interact across space and time in a North African Mediterranean ecosystem?

2. LITERATURE REVIEW

2.1. Climate Change and Mediterranean Environments

Climate change represents one of the most significant environmental challenges of the 21st century, with the Mediterranean Basin identified as a primary climate change hotspot. This region is experiencing warming at a rate approximately 20% faster than global averages (Cramer et al., 2018). Global mean temperature has increased by approximately 0.85°C over the period 1880-2012, with each of the last three decades being successively warmer than any preceding decade since 1850 (Turco et al., 2014) as illustrated in Figure 1.

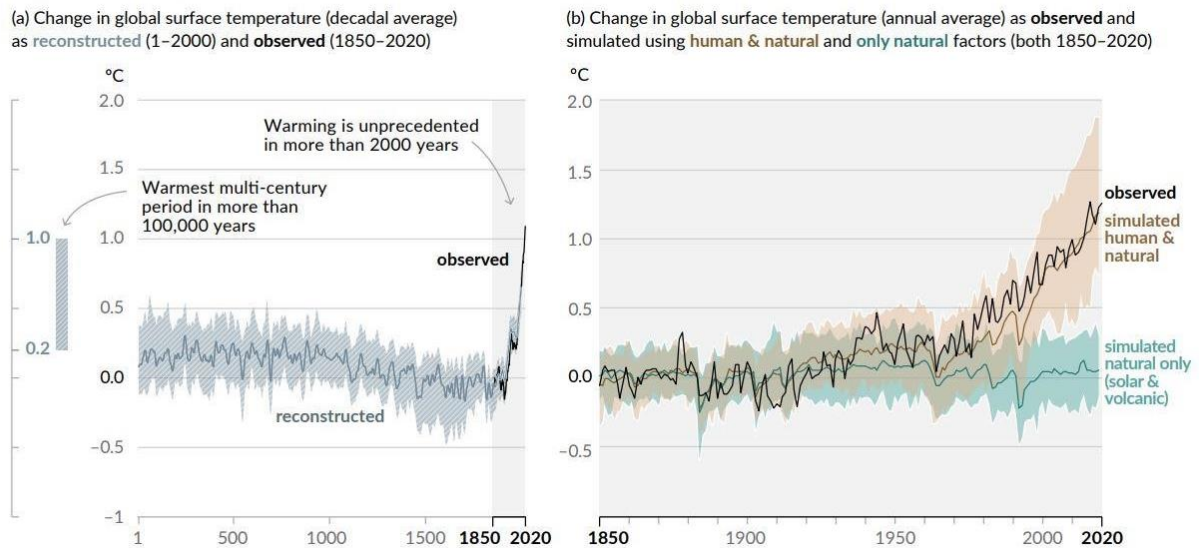


Figure 1: Changes in Global Surface Temperature (1850-2020) (Kumareswaran & Jayasinghe, 2023)

The Mediterranean climate, characterized by hot, dry summers and mild, wet winters, is projected to experience increasingly extreme seasonal contrasts. Vicente-Serrano et al. (2014) documented a warming rate of approximately 0.3°C per decade since the 1970s in many Mediterranean areas, exceeding global averages. This warming has been accompanied by decreasing annual precipitation totals in many regions, with particularly significant declines observed in the southern and eastern Mediterranean basin, including North Africa. The combination of increasing temperatures and decreasing precipitation has intensified drought conditions across much of the region, with drought severity increasing significantly even in areas where precipitation changes have been modest, due to increased evaporative demand associated with higher temperatures.

North Africa represents a particularly vulnerable subregion within the broader Mediterranean Basin. Climate models consistently project increasing temperatures and decreasing precipitation across most of North Africa through the 21st century. Tabari and Willems (2018) identified particularly strong warming signals during summer months, with projected temperature increases

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of 2-4°C by mid-century under moderate emissions scenarios and potentially exceeding 5°C by century's end under high-emission pathways. Annual precipitation is projected to decrease by 1030% across much of North Africa by mid-century, with particularly pronounced declines during spring and summer months (Tramblay et al., 2020). The eastern and southern Mediterranean regions, including Algeria, are likely to experience the most significant precipitation reductions, coupled with increased variability in precipitation events and potential intensification of extreme rainfall despite overall drying trends.

The combined effects of warming temperatures and changing precipitation patterns are projected to significantly alter drought regimes across North Africa. Drought frequency, duration, and severity are expected to increase substantially across the region, with particularly pronounced changes in semi-arid transition zones where marginal conditions already prevail (Tramblay et al., 2020). These projected changes in drought regimes have profound implications for ecosystem dynamics, agricultural productivity, and wildfire risk across North African landscapes.

Algeria has experienced significant climate changes in recent decades, with particularly pronounced impacts in its northern regions where Mediterranean forests and most of the population are concentrated. According to Slimani et al. (2014), mean annual temperatures in northern Algeria increased by approximately 1.5°C over the period 1950-2010, with accelerated warming evident since the 1980s. The Tlemcen region in northwestern Algeria represents an area of particular vulnerability due to its location in a transitional zone between Mediterranean and semi-arid climates. Belgherbi and Benabdeli (2021) noted that the region has experienced significant warming and increasingly irregular precipitation patterns in recent decades, creating more favorable conditions for wildfire ignition and spread. Climate projections for Algeria indicate continued warming and drying trends through the 21st century, with temperature increases of 23°C by mid-century and potential precipitation decreases of 10-20% across northern Algeria (Meddour-Sahar, 2015).

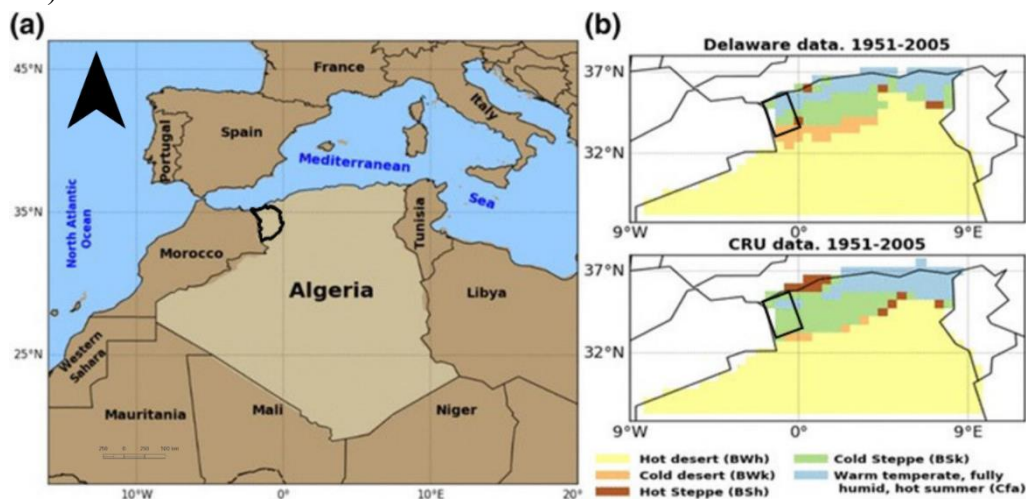


Figure 2: Geographic Location of Algeria and Köppen-Geiger Climate Classification (Zeroual et al., 2019)

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2.2. Forest Ecosystems in Mediterranean North Africa

2.2.1. Ecological characteristics of mediterranean forests

Mediterranean forest ecosystems are characterized by distinctive adaptations to the region's climate regime, with its characteristic hot, dry summers and mild, wet winters. According to Pausas and Vallejo (1999), these ecosystems have evolved through millennia of adaptation to both climate constraints and human impacts, developing remarkable resilience to various disturbances, particularly fire. Mediterranean forests typically feature sclerophyllous vegetation with physiological and morphological adaptations to seasonal drought stress, including deep root systems, thick cuticles, small leaf size, and various water conservation mechanisms. These adaptations allow Mediterranean forest species to withstand extended dry periods while maintaining ecological function and recovery capacity following disturbances.

The structure and composition of Mediterranean forests reflect complex interactions between climate, topography, substrate, and disturbance history. Keeley et al. (2011) described the typical vertical structure of Mediterranean forests, which often includes a tree layer dominated by drought adapted conifers (e.g., *Pinus halepensis*) or sclerophyllous broadleaved species (e.g., *Quercus ilex*, *Q. suber*), an extensive shrub layer comprising diverse woody species, and a seasonal herbaceous ground layer. This structural complexity contributes to the remarkable biodiversity of Mediterranean forest ecosystems, which harbor approximately 10% of the world's vascular plant species despite covering less than 2% of global land area. Notably, many Mediterranean plant species exhibit specific adaptations to fire, including serotinous cones, fire-stimulated germination, resprouting capacity, and thick insulating bark that enable population persistence in fire-prone landscapes.

Mediterranean forests provide numerous ecosystem services of critical importance to human communities in the region. Pausas and Vallejo (1999) highlighted several key services including watershed protection, erosion control, carbon sequestration, biodiversity conservation, and various provisioning services such as timber, fuelwood, cork, resins, medicinal plants, and edible products. Additionally, these forests offer important cultural and recreational values, particularly in increasingly urbanized Mediterranean societies. However, Keeley et al. (2011) emphasized that the provision of these ecosystem services is strongly influenced by forest condition, with degraded forests providing reduced services compared to healthy, functional ecosystems. This relationship underscores the importance of sustainable management approaches that maintain forest health and resilience in the face of multiple pressures including climate change, land use transformations, and altered disturbance regimes.

The ecological functioning of Mediterranean forests is strongly regulated by fire dynamics that shape vegetation structure, composition, and succession patterns. Tessler et al. (2016) examined vegetation recovery following recurrent fires in the Eastern Mediterranean, documenting the remarkable resilience of many Mediterranean forest communities to periodic burning. Their research demonstrated that many Mediterranean ecosystems maintain biodiversity and structural

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complexity despite fire disturbance through various regeneration mechanisms, though noting that recovery capacity may be compromised by changing fire regimes associated with climate change and human activities. These findings align with the fundamental ecological principles established by Keeley et al. (2011), who characterized fire as an integral ecological factor in Mediterranean ecosystems rather than an external disturbance, with many ecological processes and biodiversity patterns directly linked to historical fire regimes.

2.2.2. Algerian forest ecosystems: distribution, composition, and ecological importance

Algerian forest ecosystems cover approximately 4.1 million hectares (DGF, 2023), representing less than 2% of the national territory, with most forested areas concentrated in the northern part of the country where Mediterranean climate conditions prevail. According to Meddour-Sahar (2015), these forests form a discontinuous band extending from the Moroccan border in the west to the Tunisian border in the east, primarily distributed along the coastal plains, Tell Atlas Mountains, and high plateau regions. The distribution of forest types follows climate and topographic gradients, with species composition varying from humid coastal zones to semi-arid interior regions. This limited forest cover represents a significant conservation challenge, particularly given the ecological and socioeconomic importance of these ecosystems within a predominantly arid national context.

The composition of Algerian Mediterranean forests is characterized by both similarities to and distinctions from other Mediterranean forest ecosystems. Slimani et al. (2014) described the primary forest types in northern Algeria, which include Aleppo pine (*Pinus halepensis*) forests covering approximately 50% of the forested area, various oak forests (*Quercus suber*, *Q. ilex*, *Q. faginea*, *Q. canariensis*) comprising about 30%, and other formations including Atlas cedar (*Cedrus atlantica*), maritime pine (*Pinus maritima*), and juniper (*Juniperus spp.*) forests making up the remainder, as depicted in Figure 3. This composition reflects the region's biogeographical position within the broader Mediterranean Basin, with common Mediterranean elements alongside North African endemic or sub-endemic species. Slimani et al. (2014) particularly highlighted the ecological importance of Atlas cedar forests, which represent relict populations of high conservation value due to their genetic uniqueness, biodiversity significance, and vulnerability to climate change.

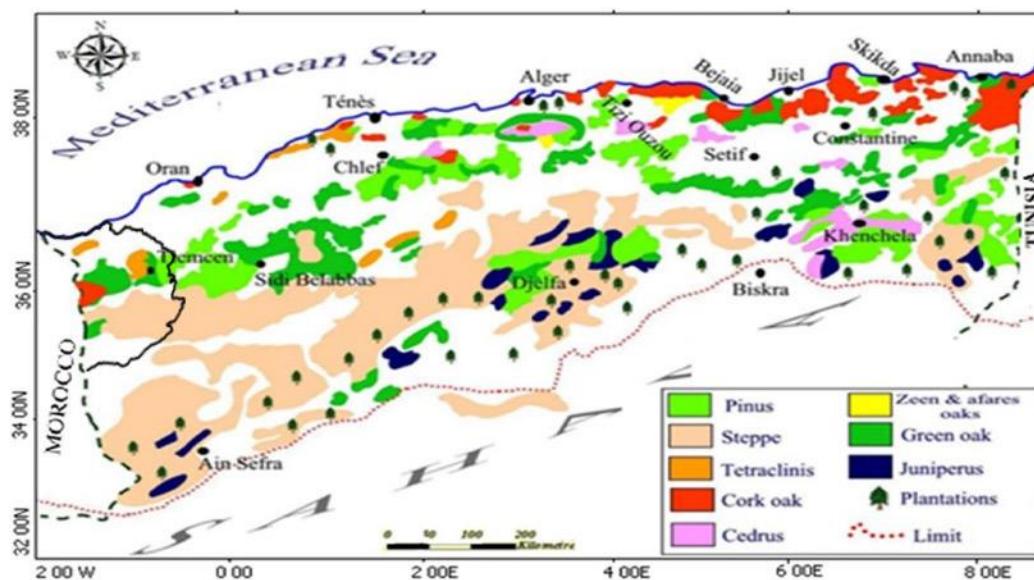


Figure 3: Distribution of Major Forest Species in Algeria (Source: Bentchakal et al., 2022)

Algerian forest ecosystems provide multiple ecological services that support both natural systems and human communities. Meddour-Sahar (2015) emphasized their crucial role in water regulation, soil protection, and microclimate regulation, particularly in mountainous regions prone to erosion and desertification. These hydrological services are especially important in the semi-arid context of northern Algeria, where forests help maintain watershed function and reduce flood risk in populated areas. Additionally, Algerian forests support remarkable biodiversity, including numerous endemic and threatened species of both flora and fauna, contributing significantly to the country's natural heritage and Mediterranean Basin biodiversity hotspot status. The ecological importance of these forests extends to their role in climate regulation through carbon sequestration, though this carbon reservoir faces increasing threats from degradation, fragmentation, and fire disturbance.

Despite their ecological significance, Algerian forest ecosystems face multiple pressures that threaten their long-term sustainability. Meddour-Sahar and Derridj (2012) documented significant forest degradation and loss across northern Algeria, with approximately 16,000 hectares lost annually due to various factors including wildfires, agricultural expansion, overgrazing, urbanization, and infrastructure development. Their analysis highlighted the particular impact of recurrent wildfires, which affected over 910,000 hectares between 1985 and 2010, often resulting in permanent conversion to shrubland or degraded formations in severely or repeatedly burned areas. These pressures have resulted in significant fragmentation of forest landscapes, reduction in mature forest area, and simplification of forest structure in many regions, with consequent impacts on biodiversity, ecosystem function, and service provision.

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2.2.3. Forest resources in the province of Tlemcen: historical and current state

The Province of Tlemcen in northwestern Algeria contains significant forest resources that reflect both the region's natural environmental conditions and historical human influences. According to Belgherbi and Benabdeli (2021), forests in Tlemcen cover approximately 144,000 hectares, representing 25% of the province's total area, with the majority of forests concentrated in the northern mountainous regions where precipitation is sufficient to support Mediterranean forest ecosystems. This relatively high forest cover compared to the national average reflects the region's favorable climate conditions and topographical diversity, though forest distribution is highly heterogeneous across the province's diverse environmental gradients.

The current forest resource distribution in Tlemcen has been significantly shaped by historical land use patterns and management interventions. Belgherbi and Benabdeli (2021) noted that many current forest stands originated from reforestation projects implemented during the colonial period and early independence years, particularly extensive Aleppo pine plantations established on degraded lands. These human-influenced forests coexist with remnant natural forest formations, creating a complex mosaic of different forest types, age structures, and ecological conditions across the landscape. Slimani et al. (2014) provided additional historical context by documenting how past exploitation patterns, including selective harvesting of valuable species, charcoal production, and conversion to agricultural uses, have significantly influenced current forest composition and condition in many areas.

The composition of forest resources in Tlemcen reflects the region's position within the broader Mediterranean biogeographical context. According to Belgherbi and Benabdeli (2021), Aleppo pine (*Pinus halepensis*) dominates many forest areas, particularly at mid-elevations, constituting approximately 60% of the total forest cover. Various oak species, primarily holm oak (*Quercus ilex*) and cork oak (*Quercus suber*), form the second major forest type, becoming more prevalent in more mesic sites and at higher elevations. The understory typically includes diverse Mediterranean shrub species such as *Pistacia lentiscus*, *Phillyrea angustifolia*, *Arbutus unedo*, and various aromatic plants including *Rosmarinus officinalis* and *Thymus* species. This vertical complexity creates important habitat structure for diverse fauna, though Belgherbi and Benabdeli (2021) noted significant variation in structural development and ecological condition across different forest areas, reflecting diverse management histories and disturbance impacts.

Forest resources in Tlemcen provide various ecosystem services of significant importance to local communities and regional environmental quality. Meddour-Sahar (2015) highlighted the importance of these forests for watershed protection in a region characterized by seasonal water scarcity and periodic flooding, with forest cover helping regulate water flows and reduce erosion on steep slopes. Additionally, forests provide important economic resources for local communities, including timber, fuelwood, non-timber forest products such as honey and medicinal plants, and increasingly, recreational and ecotourism opportunities. However, Belgherbi and Benabdeli (2021) emphasized that the provision of these ecosystem services is threatened by multiple pressures

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including recurrent wildfires, overgrazing in accessible areas, unregulated harvesting, and climate change impacts, which collectively affect forest health, regeneration capacity, and long-term sustainability.

2.2.4. Anthropogenic pressures and management challenges in Tlemcen's forests

The forests of Tlemcen Province, including those within Tlemcen National Park, face multiple anthropogenic pressures that pose significant management challenges. Leone et al. (2009) analyzed human factors of fire occurrence in Mediterranean regions, identifying various activities that contribute to fire ignition and spread in contexts similar to Tlemcen. These include agricultural burning, pastoral practices such as vegetation clearing for grazing improvement, recreational activities, discarded cigarettes, and in some cases deliberate arson related to land use conflicts or other socioeconomic factors. Meddour-Sahar et al. (2013) specifically examined forest fire causes in northern Algeria using the Delphi method with fire management experts, confirming that human activities represent the source of approximately 95% of wildfire ignitions in the region. Their analysis documented how changing land use patterns and socioeconomic conditions have altered traditional human-fire relationships, often increasing ignition risk while simultaneously reducing landscape management practices that historically limited fire spread.

Beyond fire ignitions, broader land use pressures significantly affect forest ecosystems in Tlemcen. Meddour-Sahar (2015) documented how agricultural expansion, urban development, infrastructure construction, and increased recreational use have contributed to forest fragmentation and degradation across northern Algeria, including the Tlemcen region. Additionally, changing pastoral practices, particularly the decline of traditional rotational grazing systems in favor of more intensive and less regulated approaches, have increased pressure on accessible forest areas. These various human activities interact with forest ecosystems in complex ways, often creating cumulative impacts that exceed the effects of any single pressure. The resulting landscape transformation has important implications for biodiversity patterns, ecosystem function, and wildfire risk, with fragmented and degraded forests typically more vulnerable to further degradation through positive feedback mechanisms.

Climate change represents an additional pressure that interacts with and often exacerbates other anthropogenic impacts on Tlemcen's forests. Sarris et al. (2011) examined climate change impacts on Mediterranean forest tree growth, demonstrating how increasing drought stress affects forest productivity, regeneration capacity, and vulnerability to disturbances including fire and pest outbreaks. Their research documented declining growth trends in multiple Mediterranean tree species associated with warming temperatures and increasing water limitation, suggesting reduced resilience to additional stressors. When combined with direct human pressures, these climate-induced physiological constraints create significant challenges for forest ecosystem sustainability, potentially leading to threshold responses where forests may transition to alternative, typically less complex vegetation states following disturbances.

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Management challenges in Tlemcen's forests are further complicated by institutional and governance factors. Meddour-Sahar (2015) reviewed wildfire management challenges in Algeria, identifying significant limitations in current policies and practices that constrain effective forest conservation. Their assessment noted that forest management has historically emphasized production objectives and fire suppression rather than integrated ecosystem management, with limited consideration of social dimensions, insufficient community involvement, and inadequate coordination between different stakeholders and government agencies. These institutional challenges limit the effectiveness of forest management efforts, particularly in the context of increasing environmental pressures and limited financial and technical resources. Similarly, Moreira et al. (2020) emphasized the need for paradigm shifts in Mediterranean wildfire management more broadly, advocating for approaches that better integrate ecological understanding, social dimensions, and climate adaptation considerations.

Despite these challenges, there are emerging opportunities for improved forest management in Tlemcen. San-Miguel-Ayanz et al. (2022) documented evolving forest management approaches across Mediterranean regions including North Africa, noting increasing emphasis on integrated landscape management, stakeholder participation, and resilience-based strategies that consider multiple objectives and disturbance factors simultaneously. These emerging approaches recognize the fundamental connections between forest health, fire regimes, climate conditions, and human activities, seeking more holistic management frameworks that address underlying drivers rather than symptoms alone. For Tlemcen specifically, such integrated approaches could help address the complex challenges facing forest ecosystems through better coordination between protected area management, forestry operations, agricultural practices, and urban planning, creating more sustainable landscape patterns that support both conservation objectives and human needs in the context of changing environmental conditions.

2.3. Wildfires in Mediterranean Environments

2.3.1. Fire ecology in mediterranean ecosystems

Fire represents a fundamental ecological process in Mediterranean ecosystems, shaping vegetation structure, composition, and dynamics over evolutionary timescales. According to Pausas and Vallejo (1999), Mediterranean vegetation has co-evolved with fire over millennia, developing various adaptations that enable persistence and recovery following burning. These adaptations include serotinous cones in some pine species that release seeds in response to fire, resprouting capabilities in many hardwood species, fire-enhanced germination in numerous shrub and herbaceous plants, and thick bark that provides thermal protection for mature trees. These traits reflect the long history of fire as an integral ecological factor in Mediterranean regions, where natural ignitions and, more recently, human-caused fires have been recurrent disturbances for thousands of years.

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Table 1: Fire Ecology Characteristics in Mediterranean Ecosystems (Pausas and Vallejo, 1999; Keeley et al., 2011)

Adaptation/Characteristic	Description	Example Species/Regions
Serotinous cones	Cones that release seeds in response to fire	Some pine species (e.g., <i>Pinus halepensis</i>)
Resprouting capabilities	Ability to regenerate from surviving root systems after fire	Many hardwood species (e.g., <i>Quercus</i> species)
Fire-enhanced germination	Seeds requiring fire cues (heat, smoke) to germinate	Various shrub species in matorral communities
Thick insulating bark	Provides thermal protection for mature trees	Cork oak (<i>Quercus suber</i>)
Fire regime types	Different frequency, intensity, and seasonality patterns	Mixed-severity regimes common in Mediterranean basin
Ecological effects	Varies by fire characteristics and vegetation type	Creates habitat heterogeneity and diversity

These adaptive traits, summarized in Table 1, reflect evolutionary processes shaped by fire in Mediterranean landscapes. Keeley et al. (2011) demonstrated that these adaptations influence how vegetation responds to different fire regimes—defined by frequency, intensity, seasonality, and spatial patterns. Research by Tessler et al. (2016) further showed that recovery patterns after fire events depend on specific burn characteristics, inter-fire intervals, and post-fire environmental conditions, highlighting the complex relationship between Mediterranean plants and fire disturbance.

The fire ecology of Mediterranean ecosystems encompasses important feedbacks between vegetation, climate, and fire regimes. Pausas and Fernández-Muñoz (2012) documented fundamental shifts in Western Mediterranean fire regimes associated with changing climate and land use conditions, identifying transitions from historically fuel-limited regimes to increasingly drought-driven regimes in many areas. Their research demonstrated how vegetation characteristics—including structure, biomass accumulation rates, and species composition—influence fire behavior and effects, while fire patterns in turn shape subsequent vegetation development. These bidirectional relationships create complex system dynamics with potential for both stabilizing feedbacks that maintain resilient ecosystems and destabilizing feedbacks that can

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lead to alternative ecosystem states following disturbance, particularly when multiple stressors operate simultaneously or when novel conditions exceed historical parameters.

2.3.2. Historical fire regimes in the mediterranean basin

Historical fire regimes in the Mediterranean Basin have been shaped by the complex interactions between climate variations, vegetation dynamics, and human activities over millennia. Keeley et al. (2011) provided important historical context for understanding Mediterranean fire regimes, noting that natural fire regimes in the region were historically characterized by relatively infrequent lightning-ignited fires occurring primarily during summer drought periods. These natural fires typically created a patchy mosaic of burn severities and vegetation ages across the landscape, with fire return intervals varying widely depending on climate, vegetation, and topographic factors. However, human influence on fire regimes began approximately 10,000 years ago with the spread of agriculture and pastoralism, gradually increasing ignition frequencies and altering fire seasonality patterns as humans used fire for various land management purposes.

As shown in Table 2, the human-fire relationship in Mediterranean landscapes evolved significantly over millennia. Leone et al. (2009) documented how traditional cultures developed sophisticated fire management practices that regulated burning according to seasonal conditions and community needs, creating cultural fire regimes that often-maintained landscape heterogeneity while limiting extreme fire behavior.

The distinctive historical fire regimes of Mediterranean North Africa, including regions such as northern Algeria, reflect the region's specific environmental and cultural characteristics. Slimani et al. (2014) reconstructed fire history in Atlas cedar forests of northern Algeria, documenting historical fire patterns through dendrochronological methods. Their analysis revealed significant temporal variability in historical fire occurrence, with periods of more frequent burning typically associated with drier climate intervals and changes in human land use practices. Notably, their research identified periods of altered fire regimes associated with major cultural and political transitions, including changes in forest management approaches during colonial periods that often-disrupted traditional fire-human relationships. These findings highlight the importance of considering both environmental and socio-political factors when interpreting historical fire patterns and their implications for contemporary management.

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Table 2: Historical Fire Regime Changes in the Mediterranean Basin (Keeley et al., 2011; Leone et al., 2009)

Time Period	Dominant Fire Regime	Human Influence	Ecological Impact
Pre-human	Infrequent lightning-ignited fires	Minimal	Natural patch mosaic
Early agriculture (10,000 years ago)	Increasing frequency, changed seasonality	Intentional burning for land clearing	Altered species composition
Traditional Mediterranean cultures	Regulated burning, cultural fire regimes	Burning for agriculture, pasture	Maintained landscape heterogeneity
19th-20th century	Disrupted traditional patterns	Urbanization, rural depopulation, fire suppression	Increased fuel accumulation
Late 20th century to present	Fewer but larger fires	Fire suppression policies, land abandonment	Homogenized landscapes, extreme fire risk

The 19th and 20th centuries brought profound changes to Mediterranean fire regimes. Koutsias et al. (2016) documented how traditional mosaic landscapes homogenized as agricultural practices changed and rural areas depopulated. Simultaneously, fire suppression policies attempted to exclude fire from Mediterranean landscapes, creating additional changes in vegetation structure and fire behavior patterns.

2.3.3. Recent trends in mediterranean wildfire activity

Recent decades have witnessed significant changes in wildfire activity across the Mediterranean Basin, reflecting the complex influences of changing climate conditions, vegetation characteristics, and human factors. Turco et al. (2018) analyzed trends in Mediterranean wildfire activity, documenting substantial spatial and temporal variability but identifying several consistent patterns across the region. Their research noted a general increase in the number of extreme fire weather days since the 1970s, associated with warming temperatures and more frequent drought conditions. However, actual fire activity trends have shown mixed patterns, with decreasing numbers of fires and burned area in some European Mediterranean countries (particularly Spain, France, and Italy) since the 1990s, contrasted with stable or increasing trends in North African countries including Algeria. These divergent trends highlight the importance of both climate and human factors in

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determining fire activity patterns, with improved detection and suppression capabilities potentially offsetting increasing climatic fire potential in some regions.

Despite overall decreasing trends in some regions, Fernandes et al. (2016) found that extremely large wildfires (>500 hectares) have remained stable or even increased in frequency. These extreme events, which typically occur during severe fire weather periods, often exceed suppression capabilities and account for a disproportionate share of total burned area.

Table 3: Recent Fire Trends in Different Mediterranean Regions (1990-2019) (Turco et al., 2018; Fernandes et al., 2016)

Region	Fire Frequency Trend	Burned Area Trend	Key Drivers	Notable Patterns
Spain, France, Italy	Decreasing	Decreasing	Improved detection and suppression	Larger proportion of area burned in extreme events
Portugal	Variable	Increasing extreme events	Rural abandonment, climate extremes	Very large fires (>500 ha) increasing
Greece	Variable	Increasing	Climate warming, fuel continuity	Strong seasonality, concentrated in summer
North Africa (including Algeria)	Stable to increasing	Variable by subregion	Climate change, reduced management	Significant spatial clustering
Eastern Mediterranean	Variable	Increasing	Drought conditions, land use changes	Strong correlation with climate indices

Spatial analysis by Ganteaume and Barbero (2019) revealed significant regional differences in fire patterns even within countries, underscoring the importance of local context when interpreting broader trends. Their research particularly emphasized how landscape fragmentation mediates fire spread potential, with heterogeneous landscapes typically experiencing different fire size distributions than more homogeneous areas.

Climate factors have played an increasingly important role in shaping recent Mediterranean fire activity. Fox et al. (2018) analyzed relationships between wildfire risk, urban planning, and Fire Weather Index in southeastern France, documenting strengthening correlations between climate

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variables and fire occurrence over the period 1990-2013. Their research demonstrated that fire climate relationships have intensified in recent decades, with drought conditions and high temperatures becoming more dominant drivers of fire activity relative to other factors. This trend, illustrated in Figure 4, reflects both the direct effects of changing climate conditions on fuel moisture and fire behavior, as well as indirect effects mediated through vegetation responses to climate change.

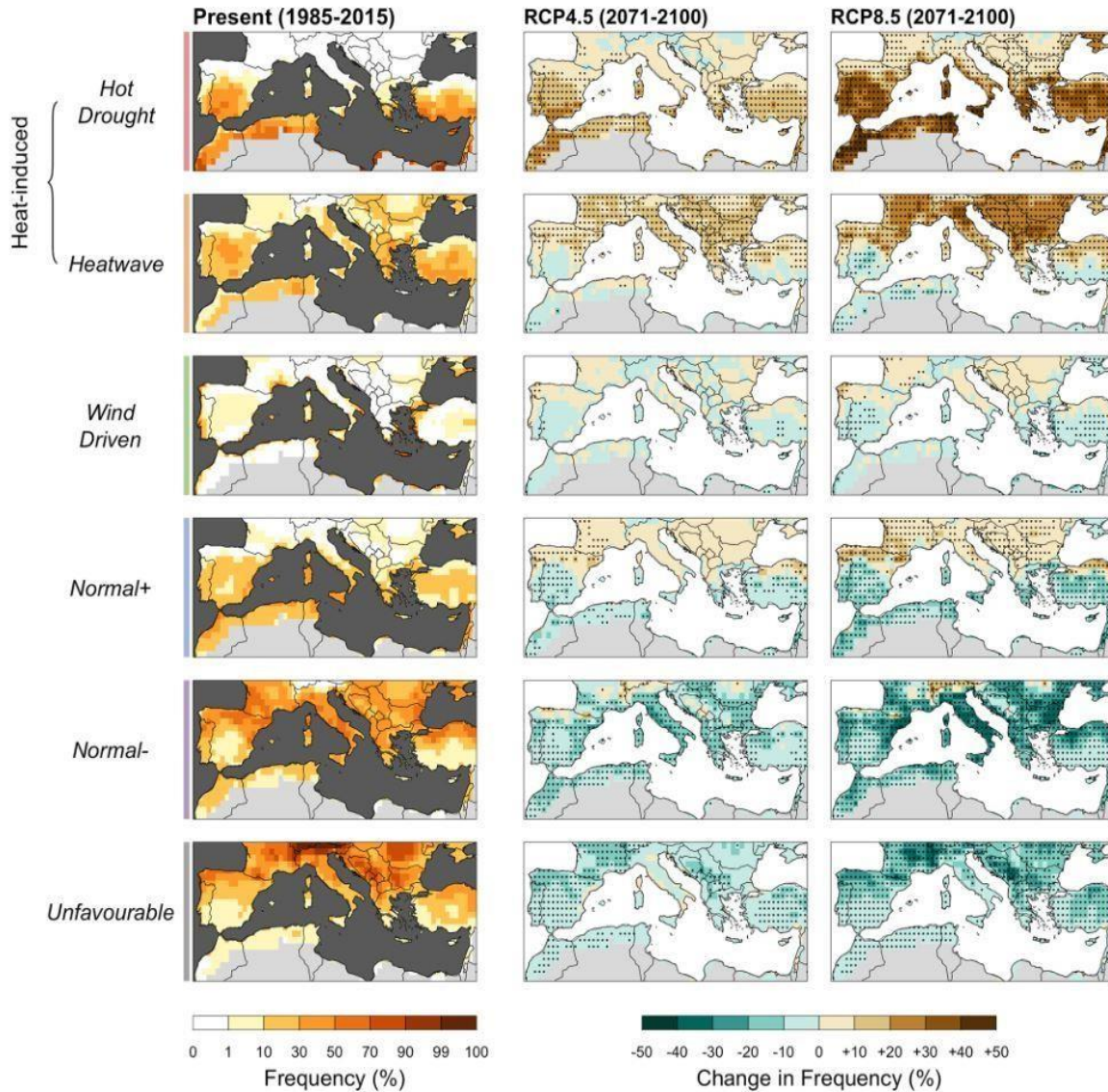


Figure 4: Increasing Likelihood of Heat-Induced Large Wildfires in the Mediterranean Basin (Ruffault et al., 2020)

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2.3.4. The 2015 and 2021 wildfire episodes in Algeria: causes and impacts

Algeria has experienced several catastrophic wildfire episodes in recent years, with the 2015 and 2021 fire seasons representing particularly severe manifestations of the changing fire dynamics affecting Mediterranean North Africa. According to Meddour-Sahar (2015), the 2015 fire season was characterized by abnormally high temperatures and extended drought conditions that created exceptionally favorable conditions for fire ignition and spread. Their analysis documented over 2,000 separate fire incidents across northern Algeria during the summer of 2015, affecting more than 37,000 hectares of forest and shrubland. The Tlemcen region was particularly impacted, with multiple large fires burning in and around Tlemcen National Park during July and August 2015, causing significant ecological damage and threatening nearby communities. These events highlighted the increasing vulnerability of Algerian landscapes to extreme fire conditions associated with climate change, particularly during periods when meteorological conditions, fuel accumulation, and human activities align to create high-risk scenarios.

The 2021 fire season, as detailed in Table 4, represented an even more extreme event with unprecedented impacts. San-Miguel-Ayanz et al. (2022) documented how exceptional heat waves combined with severe drought created catastrophic burning conditions, resulting in the highest human casualties and ecological damage recorded in Algeria's recent fire history.

Table 4: Major Fire Episodes in Algeria (2000-2021) (Meddour-Sahar, 2015; San-Miguel-Ayanz et al., 2022)

Year	Area Burned	Regions Most Affected	Weather Conditions	Human Impacts	Ecological Impacts
2015	>37,000 ha	Northern Algeria, including Tlemcen	Abnormally high temperatures, extended drought	Community evacuations, infrastructure damage	Significant degradation of forest ecosystems, soil erosion
2021	>100,000 ha	Northern provinces	Exceptional heat wave (>45°C), severe drought	90 human fatalities, extensive infrastructure damage	High-severity burning, damaged seed banks, compromised regeneration
Other significant years (2012, 2017)	Varied	Mostly northern coastal provinces	Hot, dry conditions	Variable economic losses	Cumulative impacts on forest resilience

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Both fire episodes shared certain causal elements while differing in others. Critical factors included extreme weather conditions, fuel accumulation from limited management, and various human ignition sources. However, the 2021 events involved more complex ignition patterns and more extreme meteorological conditions than the 2015 fires.

The ecological and socioeconomic impacts extended beyond the immediate burn periods. Belgherbi and Benabdeli (2021) documented variable ecological effects depending on fire severity, with high-severity areas experiencing substantial soil erosion and reduced regeneration potential. Long-term consequences included impacts on forest-dependent livelihoods, disrupted ecosystem services, and significant psychological trauma in affected communities.

2.3.5. Fire history and patterns in the province of Tlemcen

The Province of Tlemcen has experienced a complex fire history shaped by both natural and anthropogenic factors. Belgherbi and Benabdeli (2021) conducted a structural analysis of burnt areas by forest fires in Tlemcen National Park, providing important context on fire patterns in the broader region. Their research documented significant fire activity in Tlemcen over recent decades, with approximately 30% of the forested area affected by at least one fire during the period 1990-2020. This fire activity has shown considerable spatial and temporal variability, with certain areas experiencing recurrent burning while others have remained relatively fire-free. This heterogeneous fire history has contributed to the complex vegetation mosaic currently observed across the landscape, with different areas reflecting distinct fire histories and successional trajectories.

Temporal patterns of fire activity in Tlemcen show important seasonal and interannual variations. Meddour-Sahar and Derridj (2012) analyzed spatiotemporal patterns of forest fires across northern Algeria including the Tlemcen region, documenting the strong seasonality of fire occurrence. Their research indicated that approximately 80% of fires in the region occur during the summer months (June-September), with peak activity typically in July and August when temperature maximums coincide with minimum fuel moisture levels. Interannual variations in fire activity show significant correlations with climate conditions, particularly summer temperature anomalies and preceding winter-spring precipitation patterns that influence fuel accumulation and moisture content. However, they also noted important human influences on temporal patterns, including increased ignitions associated with agricultural activities during harvest periods and recreational use during holidays.

The spatial distribution of fire activity in Tlemcen reflects interactions between biophysical and human factors. Belgherbi and Benabdeli (2021) analyzed spatial patterns of fire occurrence, identifying several factors that influence fire distribution in the region. Their research documented higher fire frequencies in areas characterized by specific combinations of topographic variables (particularly south-facing slopes and ridge positions), vegetation characteristics (dominated by

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fire-prone species such as Aleppo pine with dense understory vegetation), and human access (proximity to roads, settlements, and agricultural areas). Figure 5 shows the broader patterns of fire occurrence across Northern Algeria, with notable spatial clustering that reflects these biophysical and anthropogenic influences.

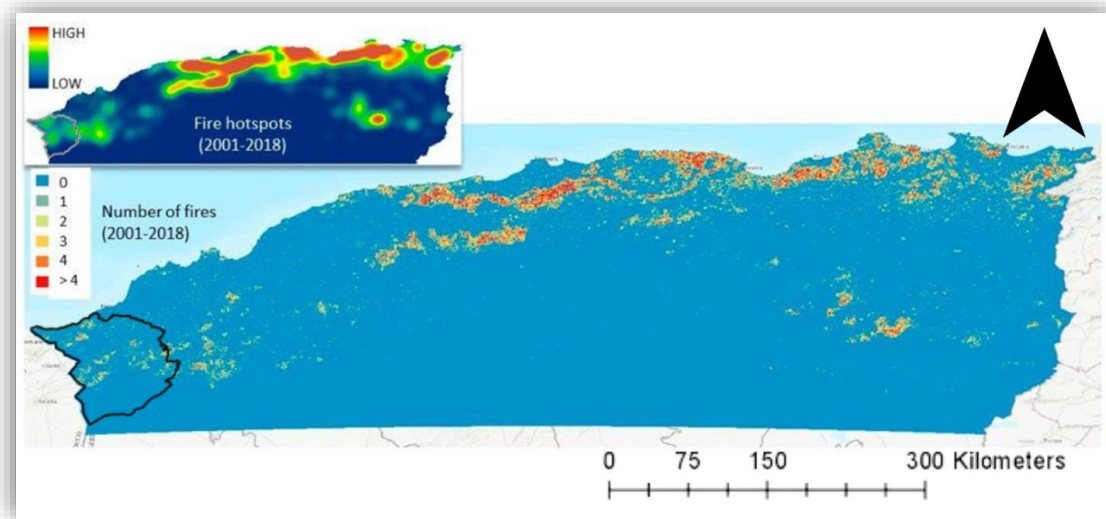


Figure 5: Spatial Distribution of Fire Occurrence in Northern Algeria (2001-2018) (Curt et al., 2020)

Human factors play a dominant role in determining fire patterns in Tlemcen. Meddour-Sahar et al. (2013) analyzed forest fire causes in northern Algeria, documenting the overwhelmingly anthropogenic origin of ignitions in the region. Their research using the Delphi method with fire management experts identified various human activities responsible for fire starts, including agricultural burning (particularly stubble burning), discarded cigarettes, campfires, land clearing for development, conflicts related to land use rights, and in some cases deliberate arson associated with various motivations. These human ignition sources showed spatial patterns strongly correlated with accessibility and human use intensity, with particularly high ignition densities in wildland-urban interface zones where human activities directly intermingle with flammable vegetation. This human dimension of fire patterns has important implications for prevention strategies, suggesting the need for targeted interventions addressing specific high-risk activities and areas rather than uniform approaches across the landscape.

The fire history of Tlemcen provides important context for current management challenges and future fire risk projections. Meddour-Sahar (2015) emphasized how historical fire patterns have created cumulative impacts on forest ecosystems, with areas experiencing repeated burning often

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showing significant ecological changes including reduced tree cover, shifts in species composition toward more fire-adapted taxa, and in some cases, conversion to shrubland communities. These fire-driven vegetation changes create feedback effects on subsequent fire potential, with potential for both negative feedbacks (reduced fuel loads following recent fires) and positive feedbacks (increased dominance of highly flammable species in some post-fire communities). Understanding these historical patterns and their ecological consequences provides essential context for projecting future fire risk under changing climate and land use conditions, highlighting areas where targeted management interventions may be necessary to prevent further degradation or to promote ecosystem recovery following past fire impacts.

2.4. Climate-Vegetation-Fire Relationships

2.4.1. Theoretical frameworks for climate-vegetation-fire interactions

Understanding the complex relationships between climate, vegetation, and fire requires robust theoretical frameworks that capture their multidirectional interactions. Pausas and FernándezMuñoz (2012) proposed a conceptual model distinguishing between fuel-limited and drought driven fire regimes in Mediterranean environments. Their framework suggests that fire activity can be limited by either fuel availability in drier regions or by fuel dryness in more productive regions, with climate change potentially shifting these limiting factors across space and time. This model provides a foundation for understanding how climate influences both fuel production through vegetation growth and fuel flammability through moisture content.

Batllori et al. (2013) expanded this framework by incorporating vegetation dynamics and climate change projections to model potential shifts in Mediterranean fire regimes. Their approach emphasizes that climate affects fire regimes both directly through weather conditions that determine ignition probability and fire behavior, and indirectly through longer-term effects on vegetation composition, structure, and fuel characteristics.

Building on these concepts, Moreira et al. (2020) developed a more comprehensive framework that explicitly addresses climate change dimensions. Their model emphasizes feedback loops where vegetation characteristics influence fire behavior, while fire effects in turn shape subsequent vegetation development under changing climate conditions. This bidirectional relationship creates system dynamics with potential for both stabilizing feedbacks that maintain resilient ecosystems and destabilizing feedbacks that can lead to novel ecosystem states following disturbance. The authors particularly highlight the importance of understanding these feedbacks for developing effective management approaches in the context of climate change, where historical relationships may provide incomplete guidance for future conditions in Mediterranean ecosystems.

2.4.2. Climate drivers of wildfire activity in mediterranean regions

Climate represents a fundamental driver of fire activity in Mediterranean regions through direct effects on fuel flammability and indirect effects on vegetation structure and composition. Turco et al. (2018) assessed exacerbated fires in Mediterranean Europe due to anthropogenic warming, identifying several key climate variables that influence fire patterns across multiple temporal scales. At the seasonal scale, their research demonstrated strong correlations between fire activity and temperature anomalies, with warmer conditions associated with increased burning in most Mediterranean areas. Precipitation showed more complex relationships, with fire activity negatively correlated with current-season precipitation (which affects fuel moisture) but sometimes positively correlated with previous-season precipitation (which affects fuel accumulation in some ecosystems). These seasonal relationships translate into interannual variability in fire activity strongly linked to climate fluctuations, with particularly extensive fire seasons typically associated with drought years.

Drought represents a particularly critical climate driver of Mediterranean fire activity. Ruffault et al. (2018) identified specific connections between extreme wildfire events and global-change-type droughts in the northern Mediterranean, documenting how changing drought characteristics affect fire regimes. Their research distinguished between different drought syndromes associated with extreme fire events, including intense summer droughts that create short-term but extreme fire weather conditions, and longer-term precipitation deficits that progressively increase landscape flammability through cumulative vegetation stress. The increasing frequency of these drought conditions under climate change has important implications for fire management, as drought associated fires often exhibit extreme behavior that exceeds suppression capabilities regardless of fuel management efforts.

Wind patterns represent another important climate driver of fire activity, particularly for large and high-intensity fire events. Fernandes et al. (2016) analyzed characteristics and controls of extremely large wildfires in the western Mediterranean Basin, documenting the critical role of strong, dry winds in determining fire spread rates and final fire sizes. Their research identified synoptic weather patterns associated with enhanced fire risk, particularly those bringing hot, dry continental air masses across the Mediterranean region. These wind events not only directly accelerate fire spread through physical mechanisms but also rapidly reduce fuel moisture content, creating conditions where even relatively small ignitions can quickly develop into major fire events that exceed suppression capabilities.

At longer timescales, climate trends influence Mediterranean fire activity through their effects on vegetation composition, structure, and condition. Vicente-Serrano et al. (2014) documented increasing drought severity caused by temperature rise in southern Europe, identifying important implications for vegetation stress and subsequent fire risk. Their research demonstrated how warming temperatures exacerbate drought impacts on vegetation even when precipitation changes are modest, due to increased evaporative demand that accelerates moisture depletion from both

soils and plant tissues. These climate-driven changes in vegetation water status directly affect flammability while potentially leading to longer-term shifts in vegetation composition toward more drought-tolerant but often more fire-prone species. Such vegetation transformations can create novel fuel conditions that alter fire behavior characteristics and challenge established management approaches calibrated to historical conditions.

2.4.3. Vegetation health as a predictor of fire risk

Vegetation health status represents a critical link between climate conditions and fire risk, integrating the cumulative effects of multiple environmental factors into measurable indicators of ecosystem condition and potential flammability. Gouveia et al. (2016) examined the modulating effect of drought on vegetation-fire relationships in southern European ecosystems, demonstrating significant correlations between vegetation stress indicators and subsequent fire activity. Their research utilized satellite-derived vegetation indices to assess vegetation condition, finding that declining index values associated with drought stress often preceded increased fire occurrence. As shown in Figure 6, forest decline has been increasingly observed in recent years, indicating deteriorating vegetation health that corresponds with heightened fire risk conditions.

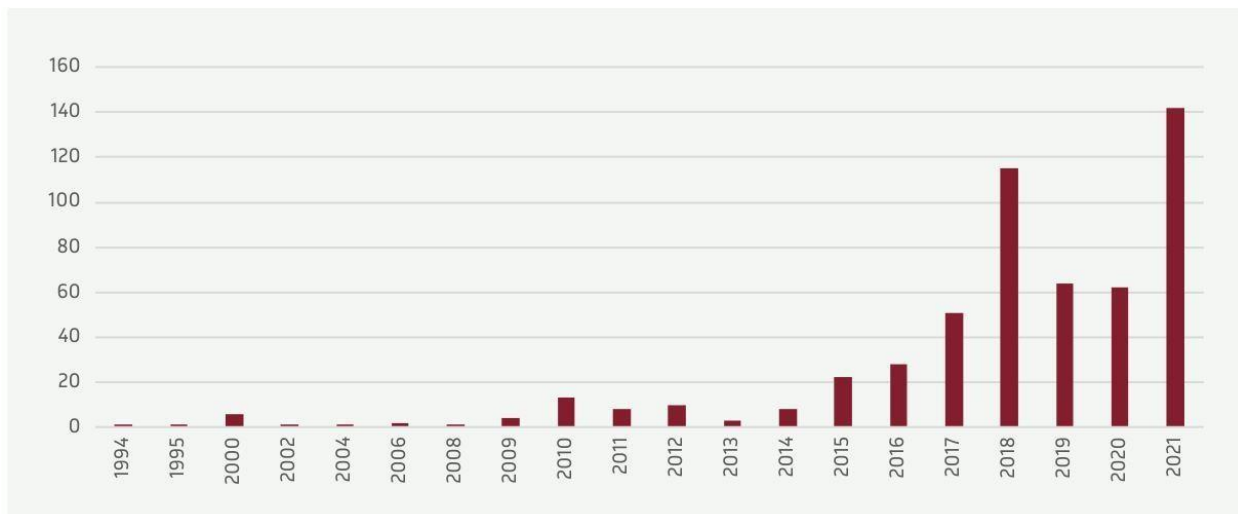


Figure 6: Number of diebacks observed annually in Algeria (DGF, 2023)

Different vegetation types exhibit varying relationships between health status and fire vulnerability. Tessler et al. (2016) examined vegetation cover and species richness after recurrent forest fires in the Eastern Mediterranean ecosystem, documenting how different plant communities show distinct responses to drought stress and subsequent fire risk. Their research identified particularly strong drought-fire relationships in pine-dominated forests, reflecting the high flammability of coniferous vegetation under water-limited conditions. In contrast, some oak dominated communities showed greater drought resistance and less dramatic increases in flammability during moderate drought periods, though still experiencing significant vulnerability

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during extreme drought events. These differential responses highlight the importance of considering vegetation composition when interpreting health indicators for fire risk assessment.

The temporal dynamics of vegetation health-fire relationships involve important lag effects that influence predictive capabilities. Gouveia et al. (2016) demonstrated that correlations between vegetation condition indices and fire activity operate across various time scales, with both immediate and delayed relationships depending on ecosystem characteristics and climate patterns. In some Mediterranean systems, rapid vegetation responses to drought create near-immediate increases in fire potential, while in others, cumulative stress over multiple months or seasons more strongly predicts subsequent fire activity. Understanding these temporal dynamics is essential for developing effective early warning systems that accurately translate vegetation health indicators into fire risk assessments with appropriate lead times for management interventions.

Remote sensing approaches have significantly advanced capabilities for monitoring vegetation health-fire relationships across broad spatial scales. Chuvieco et al. (2012) integrated geospatial information into fire risk assessment, demonstrating how satellite-derived vegetation condition metrics can be combined with other environmental variables to create comprehensive fire risk evaluation systems. Their research emphasized the value of time-series analysis for detecting anomalous vegetation conditions relative to historical baselines, enabling identification of areas experiencing unusual stress levels that may indicate elevated fire risk. These remote sensing capabilities are particularly valuable in regions with limited ground-based monitoring infrastructure, providing consistent, spatially comprehensive measurements at regular intervals that support operational risk assessment and management prioritization.

Remote sensing techniques have been widely employed to assess vegetation health and drought patterns in relation to fire risks. Santos, Bento-Gonçalves, Vieira, and Teixeira (2023) utilized MODIS fire products and European Space Agency data to examine fire activity in Mediterranean forests, including Algeria. Their study highlighted the influence of climate change and alterations in vegetation composition on fire regimes (Santos et al., 2023). Santos et al. (2023) employed logistic regression and machine learning algorithms to model and map wildfire occurrence in the Mediterranean region, considering various environmental and anthropogenic factors (Santos et al., 2023). These advanced approaches enable more precise identification of high-risk areas by integrating multiple remotely sensed variables with traditional fire risk factors.

2.4.4. Drought-Fire relationships in mediterranean forests

Drought conditions play a particularly critical role in determining fire risk in Mediterranean forest ecosystems, where seasonal water limitation already represents a defining ecological characteristic. Vicente-Serrano et al. (2010) developed the Standardized Precipitation Evapotranspiration Index (SPEI), providing a robust tool for quantifying drought severity that accounts for both precipitation deficits and temperature effects on evaporative demand. Their research demonstrated strong statistical relationships between SPEI values and subsequent fire activity across various Mediterranean regions, with particularly strong correlations at 3-6 month

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timescales. These temporal relationships suggest that cumulative drought effects over seasonal timescales, rather than short-term weather fluctuations, often establish the fundamental conditions for extensive fire activity in Mediterranean forest ecosystems.

The mechanisms through which drought influences fire risk involve complex interactions between atmospheric conditions, soil moisture dynamics, and vegetation responses. Ruffault et al. (2018) examined links between extreme wildfire events and global-change-type droughts in the northern Mediterranean, documenting how drought development typically follows a sequence from precipitation deficits to soil moisture depletion and ultimately to vegetation water stress. Their research indicated that this progression creates increasingly favorable conditions for fire ignition and spread, with maximum fire danger often occurring when atmospheric, soil, and vegetation drought conditions align. Under such circumstances, even relatively small ignition events can develop into major fires due to the enhanced flammability of live vegetation and the increased availability of dead fuels across the landscape.

Drought-fire relationships show important spatial patterns related to topographic and ecological factors. Gouveia et al. (2016) assessed how drought modulates vegetation-fire relationships in southern European ecosystems, identifying significant variability in drought exposure and sensitivity across landscapes. Their analysis revealed that south-facing slopes, ridge positions, and areas with shallow soils often experience more severe drought effects and consequently higher fire risk during dry periods. These spatial patterns interact with vegetation distribution, as drought-sensitive species or communities located in drought-prone landscape positions face particularly elevated fire risk during water-limited periods. Understanding these spatial relationships is essential for developing targeted management strategies that address specific high-risk components of heterogeneous landscapes.

Climate change is altering fundamental drought-fire relationships in Mediterranean forest ecosystems, potentially creating novel fire regime characteristics. Pausas and Fernández-Muñoz (2012) documented a shift from fuel-limited to drought-driven fire regimes in the Western Mediterranean Basin, noting how changing climate conditions have altered the primary constraints on fire activity in many areas. Their research demonstrated that while historical fire regimes in many Mediterranean regions were limited primarily by fuel continuity and accumulation following disturbance or land use changes, recent decades have seen increasing dominance of drought conditions as the primary driver of fire activity patterns. This shift reflects both direct climate effects on fire weather conditions and indirect influences through vegetation stress, with important implications for management approaches that must adapt to these changing fundamental relationships rather than relying on historical patterns alone.

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2.4.5. Climate change implications for future fire regimes

Climate change is projected to have profound implications for future fire regimes in Mediterranean regions, potentially exceeding the historical range of variability to which ecosystems and human communities have adapted. Turco et al. (2018) assessed exacerbated fires in Mediterranean Europe due to anthropogenic warming, utilizing ensemble climate model projections to estimate future fire weather conditions. Their analysis indicated substantial increases in fire danger across most Mediterranean areas under both moderate and high emissions scenarios, with particularly pronounced changes in North African regions including Algeria. These projections suggest that fire seasons will likely extend by 3-5 weeks by mid-century, with significant increases in the number of extreme fire danger days when suppression capabilities may be overwhelmed by fire behavior.

Vegetation responses to changing climate conditions will mediate future fire regime characteristics in complex ways. Batllori et al. (2013) projected climate change-induced shifts in fire for Mediterranean ecosystems, examining potential vegetation transitions under projected climate scenarios. Their research suggested that many current forest areas may experience transitions toward more xeric vegetation types as water limitations intensify, potentially altering fuel characteristics and fire behavior. While reduced vegetation density might decrease fuel continuity in some areas, increased proportions of drought-adapted, fire-prone species could enhance flammability, creating complex spatial patterns of changing fire potential across the landscape. These vegetation-mediated effects highlight the importance of considering ecological transitions rather than assuming static vegetation when projecting future fire regimes under climate change.

The combined effects of multiple climate change factors are likely to create novel fire regime conditions in many Mediterranean areas. Fernandes et al. (2016) analyzed extremely large wildfires in the western Mediterranean Basin, considering the interactive influences of changing temperature, precipitation, and wind patterns. Their modeling results indicated potential for synergistic effects where multiple changing climate parameters simultaneously enhance fire risk, potentially creating extreme fire environments beyond historical precedent. Particularly concerning is the projected increase in frequency of drought conditions coinciding with heat waves and strong winds, which historically have been associated with the most extreme fire behavior and largest fire events. These compound effects present particular challenges for management planning and risk assessment, as historical relationships between individual climate variables and fire activity may not adequately capture future fire potential under novel climate conditions.

Human adaptations and management responses will play crucial roles in determining how changing climate conditions ultimately translate into future fire regimes. Moreira et al. (2020) examined wildfire management paradigms in Mediterranean-type regions, emphasizing that climate-driven increases in fire potential can be either amplified or moderated by human actions. Their analysis highlighted how land use changes, fire management approaches, and broader socioeconomic factors will interact with climate drivers to shape future fire patterns. These human

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dimensions underscore the importance of integrated adaptation strategies that address both biophysical and socioeconomic aspects of changing fire regimes under climate change. For Mediterranean North Africa specifically, including regions such as Tlemcen, the authors emphasized the need for management approaches that recognize the projected intensity of climate change impacts while accounting for the region's specific socioeconomic context and development priorities.

2.5. Wildfire Risk Assessment Frameworks

2.5.1. Conceptual models of wildfire risk

Wildfire risk assessment requires robust conceptual frameworks that integrate multiple dimensions of risk, including hazard, vulnerability, and exposure components. Chuvieco et al. (2014) established a comprehensive conceptual model for fire risk assessment in Mediterranean environments, defining risk as the product of two main components: fire danger (the potential for fire ignition and propagation based on fuel and environmental conditions) and potential damage (the vulnerability of values-at-risk to fire effects). This framework recognizes that risk emerges from the interaction between biophysical factors that determine fire behavior and socioeconomic factors that determine potential impacts, providing a structured approach for developing integrated assessment methodologies. The authors emphasized that comprehensive risk assessment must consider both the probability of fire occurrence and the potential consequences of that occurrence, addressing the full spectrum of factors that contribute to wildfire risk in Mediterranean landscapes.

Building on this foundation, Chuvieco et al. (2012) further refined conceptual approaches to fire risk assessment, distinguishing between different temporal dimensions of risk factors. Their model separated long-term structural risk components (including topography, vegetation type, and infrastructure distribution) from short-term dynamic risk factors (such as weather conditions, fuel moisture, and seasonal human activities). This temporal differentiation enables the development of both strategic risk assessments that support long-term planning and tactical assessments that address immediate fire danger conditions. The integration of these temporal dimensions provides a more comprehensive understanding of wildfire risk that can support diverse management objectives and decision timeframes.

Salis et al. (2021) reviewed recent developments in forest fire risk mapping in Mediterranean areas, documenting the evolution of conceptual approaches from relatively simple index-based methods toward more comprehensive modeling frameworks that simulate fire-environment interactions. Their analysis traced the progression from static risk assessments based on vegetation and topography to dynamic approaches that incorporate weather variation, human factors, and potential fire behavior. These advances reflect growing recognition of wildfire risk as an emergent property of complex socio-ecological systems rather than a simple function of individual environmental variables. The resulting conceptual frameworks increasingly emphasize the importance of considering multiple risk dimensions simultaneously, including ignition probability, fire spread potential, suppression difficulty, and potential impacts on values at risk.

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Bento-Gonçalves and Vieira (2020) specifically addressed wildfire risk in wildland-urban interface (WUI) areas, developing conceptual frameworks that integrate traditional wildfire risk factors with elements particular to the built environment. Their model emphasized the importance of considering structural characteristics of human settlements, infrastructure vulnerability, evacuation constraints, and societal risk perception alongside conventional biophysical risk factors. This integrated approach recognizes the distinctive risk characteristics of interface areas where human communities directly intermingle with flammable vegetation, creating unique risk conditions that require specialized assessment frameworks. The authors particularly highlighted the importance of scale considerations in WUI risk assessment, noting that risk factors operate at different spatial scales from individual structures to landscape patterns, necessitating multi-scale assessment approaches that capture interactions across these different levels.

2.5.2. Variables and indicators used in fire risk assessment

Effective wildfire risk assessment requires appropriate variables and indicators that capture the multiple factors influencing fire occurrence, behavior, and impacts. Chuvieco et al. (2014) identified several key variable categories commonly incorporated into comprehensive risk frameworks. These include environmental variables (climate, topography, vegetation), anthropogenic variables (human presence, infrastructure, land use), historical fire patterns, and values-at-risk considerations. Their research emphasized that while core variable categories remain consistent across most assessment approaches, the specific indicators and their relative weights vary considerably depending on regional characteristics and assessment objectives. This variability reflects both the context-dependent nature of fire risk and the practical constraints of data availability that often necessitate different indicator selections in different assessment contexts.

Climate and weather variables represent critical components of most fire risk assessments. Fox et al. (2018) analyzed wildfire risk relationships with urban planning and Fire Weather Index in southeastern France, identifying key meteorological indicators including temperature, relative humidity, wind speed and direction, and precipitation. These variables are often integrated into composite fire weather indices such as the Canadian Fire Weather Index or the Forest Fire Danger Index that capture their combined influence on fire potential. Their research demonstrated strong correlations between these indices and fire occurrence in Mediterranean contexts, validating their utility for operational risk assessment. However, they also noted that index performance varies across different Mediterranean regions, highlighting the importance of regional calibration to account for specific environmental characteristics and fire regime patterns.

Vegetation characteristics provide essential information about potential fuel conditions for fire spread. Chuvieco et al. (2012) examined the integration of geospatial information into fire risk assessment, identifying several effective indicators of vegetation condition and fire susceptibility. Their research documented the utility of variables including vegetation type, biomass density, structural arrangement, and moisture content for characterizing potential fire behavior and effects.

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Remote sensing approaches have proven particularly valuable for deriving these vegetation indicators across large spatial extents, with various satellite-derived indices capturing different aspects of vegetation condition relevant to fire risk. The authors emphasized the importance of considering both static vegetation characteristics related to ecosystem type and dynamic condition factors that reflect seasonal and interannual variations in vegetation stress and moisture content.

Human factors represent increasingly important variables in comprehensive fire risk assessment. Leone et al. (2009) analyzed human factors of fire occurrence in Mediterranean regions, highlighting the need to incorporate socioeconomic indicators that capture human influence on ignition patterns. Their research identified variables such as population density, distance to roads and settlements, agricultural practices, recreational use intensity, and historical ignition patterns as significant predictors of human-caused fire occurrence. These factors are particularly important in Mediterranean contexts where human activities represent the source of 95-98% of wildfire ignitions. However, the authors noted significant challenges in quantifying and mapping some human-related variables, particularly those related to behaviors, attitudes, and cultural practices that influence fire use patterns but resist straightforward geospatial representation.

Vulnerability and exposure variables capture the potential consequences dimension of fire risk. Bento-Gonçalves and Vieira (2020) examined key concepts and evaluation methodologies for wildfires in wildland-urban interface zones, emphasizing the importance of variables that characterize potential impacts on human communities and infrastructure. Their research identified indicators including building materials and design, vegetation clearance around structures, road network characteristics for evacuation, water availability for suppression, and presence of vulnerable populations such as elderly or disabled residents. These vulnerability factors interact with hazard conditions to determine overall risk levels, highlighting the importance of integrated assessment approaches that consider both the probability of fire occurrence and the potential consequences for human communities and ecosystems. The authors particularly emphasized the value of participatory approaches for identifying locally significant vulnerability factors that may not be captured in standardized assessment frameworks.

2.5.3. Spatial and temporal scales in risk assessment

Wildfire risk assessment frameworks must operate across multiple spatial and temporal scales to effectively support different management objectives and decision contexts. Koutsias et al. (2016) examined fire occurrence zoning from local to global scale in the European Mediterranean basin, demonstrating how assessment approaches and variables change across spatial scales. Their research identified distinct assessment requirements at different scales, with fine-scale analyses (1-100 km²) typically emphasizing detailed fuel characteristics, topographic features, and specific human activities, while broader-scale assessments (1,000-10,000 km²) focus more on climate patterns, general land cover types, and regional socioeconomic factors. This multi-scale perspective recognizes that fire risk emerges from interactions between processes operating at different spatial scales, requiring assessment approaches tailored to specific application contexts.

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The importance of spatial scale considerations in risk assessment is further emphasized by their implications for management applications. Salis et al. (2021) reviewed recent developments in forest fire risk mapping, noting that different management objectives require risk information at different spatial resolutions. Their analysis highlighted that strategic planning for infrastructure development or fuel treatment prioritization typically requires moderate-resolution risk assessments covering large areas, while tactical pre-suppression planning and evacuation decision making need higher-resolution assessments of specific high-risk zones. These different applications create tradeoffs between spatial extent, resolution, and update frequency that must be considered when designing risk assessment systems. The authors particularly emphasized the value of hierarchical approaches that nest fine-scale assessments of high-priority areas within broader contextual assessments, enabling efficient allocation of limited assessment resources while maintaining appropriate detail where most needed.

Temporal scaling presents similar challenges for comprehensive risk assessment. Chuvieco et al. (2012) distinguished between different temporal components of wildfire risk, ranging from long term structural factors that change slowly over years or decades to short-term dynamic factors that vary seasonally, daily, or even hourly. Their approach separated relatively stable risk elements (topography, vegetation type, infrastructure) from temporally variable components (weather conditions, fuel moisture, seasonal human activities), enabling both long-term strategic risk assessment and short-term tactical evaluations. This temporal differentiation supports various management applications, from infrastructure planning and fuel treatment prioritization requiring stable risk assessments to daily operational decision-making needing frequent risk updates that capture changing weather conditions and fuel moisture status.

The integration of multi-scale information represents a particular challenge for comprehensive risk assessment. Bento-Gonçalves and Vieira (2020) addressed this challenge in the context of wildland-urban interface risk assessment, proposing approaches that integrate information across spatial and temporal scales. Their analysis highlighted methods such as hierarchical modeling frameworks that nest fine-scale process representations within broader-scale contexts, allowing risk assessments to capture both local detail and regional patterns. These integrated approaches better represent the cross-scale interactions that characterize actual fire dynamics in complex landscapes, though they typically require more sophisticated modeling techniques and diverse data inputs. The authors emphasized that effective multi-scale integration requires careful consideration of how risk factors and their relationships change across scales, avoiding simple extrapolation of relationships established at one scale to other scales where different processes may dominate.

2.5.4. Existing fire risk assessment systems in mediterranean countries

Various fire risk assessment systems have been implemented across Mediterranean countries, ranging from relatively simple index-based approaches to sophisticated modeling frameworks incorporating multiple risk components. San-Miguel-Ayanz et al. (2022) described the European Forest Fire Information System (EFFIS) that provides harmonized risk information across most

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European Mediterranean countries. EFFIS integrates daily fire danger ratings based on meteorological conditions with longer-term structural risk assessments based on fuel, topography, and historical fire patterns. The system produces both strategic risk maps for planning purposes and daily fire danger forecasts that support operational decision-making during fire seasons. While EFFIS provides valuable standardized information across Europe, the authors noted that its implementation in North African Mediterranean countries including Algeria remains limited, creating information gaps regarding fire risk in these regions despite their significant fire activity.

In Spain and Portugal, more advanced fire risk assessment frameworks have been developed that incorporate fire behavior modeling capabilities. Rodrigues et al. (2022) discussed wildfire assessment approaches in the Mediterranean context, referencing the comprehensive risk assessment systems operating in these countries. Their analysis noted that these systems combine weather-based indices, satellite-derived vegetation condition information, and probabilistic fire spread simulations to provide both strategic and tactical risk assessments. These approaches enable more detailed evaluation of potential fire behavior and impacts under various scenarios, supporting both pre-fire planning and active incident management. The integration of dynamic fire growth modeling with traditional risk indices represents an important advancement, enabling more realistic assessment of potential fire impacts rather than relying solely on statistical relationships between environmental conditions and historical fire patterns.

France has developed regionally calibrated risk assessment systems for its Mediterranean departments. Fox et al. (2018) analyzed wildfire risk relationships with urban planning and Fire Weather Index in southeastern France, describing the operational risk assessment approach used by French authorities. Their research outlined how the system combines a modified version of the Canadian Fire Weather Index with regional fuel maps, historical fire patterns, and infrastructure data to produce daily risk assessments at multiple scales. Particular emphasis is placed on wildland-urban interface zones where human communities directly intermingle with flammable vegetation, creating distinctive risk characteristics that require specialized assessment approaches. The French system incorporates specific adaptations for Mediterranean conditions, including adjustments for the effects of strong regional winds (Mistral) that significantly influence fire spread potential in southern France.

In North African Mediterranean countries, less formalized risk assessment approaches have typically been employed. Meddour-Sahar and Derridj (2012) conducted fire risk assessment in Algeria, documenting the primarily weather-based systems used by Algerian authorities. Their research indicated that Algerian fire risk assessment has historically relied on basic meteorological indices with limited incorporation of vegetation, topographic, or human factors. However, they noted ongoing efforts to develop more comprehensive assessment frameworks better suited to Algerian conditions, including initial applications of GIS-based approaches that integrate multiple risk components to support both strategic planning and operational decision-making. These emerging systems seek to adapt established Mediterranean risk assessment principles to the specific environmental and socioeconomic conditions of North African contexts, though

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significant implementation challenges remain related to data availability, technical capacity, and institutional structures.

2.5.5. Challenges in developing fire risk assessment for north African contexts

Developing effective fire risk assessment frameworks for North African Mediterranean contexts presents several distinctive challenges that must be addressed to support improved fire management. Meddour-Sahar (2015) examined wildfire problems and challenges in Algeria, identifying data limitations as a primary constraint for comprehensive risk assessment. Their analysis noted significant gaps in systematic information regarding historical fire patterns, detailed vegetation characteristics, and socioeconomic factors influencing fire activity. These data deficiencies complicate the development of empirically calibrated risk models and limit the validation of assessment approaches, necessitating creative methodological solutions that balance information requirements with practical data constraints. The author particularly emphasized the need for improved fire reporting systems that capture not only basic fire statistics but also information about causal factors, fire behavior, and impacts that could support more sophisticated risk assessment approaches.

Technical capacity and resource limitations present additional challenges for sophisticated risk assessment in North African contexts. Meddour-Sahar and Derridj (2012) noted constraints in computational infrastructure, specialized expertise, and operational capabilities for implementing advanced risk assessment approaches in Algeria. Their research highlighted the need for assessment frameworks that balance analytical sophistication with operational feasibility, recognizing that highly complex systems may prove difficult to implement and maintain in regions with limited technical resources. This balance requires careful consideration of local capabilities and constraints when adapting risk assessment approaches developed in other Mediterranean regions. The authors emphasized the value of phased implementation approaches that start with simpler systems addressing the most critical risk factors and gradually incorporate additional components as capacity develops.

Distinctive environmental and socioeconomic characteristics in North African Mediterranean regions necessitate specific adaptations to risk assessment frameworks. Meddour-Sahar et al. (2013) analyzed forest fire causes and motivations in northern Algeria, identifying several factors requiring particular attention in North African contexts. These include the predominance of certain forest types not common in European Mediterranean countries (e.g., Aleppo pine as the dominant conifer), more extensive semi-arid transition zones, different land use histories and practices, and unique socioeconomic factors influencing human-fire interactions. These distinctive characteristics require calibration and modification of risk assessment approaches developed in other Mediterranean regions to ensure their relevance and accuracy in North African applications. The authors particularly highlighted the importance of incorporating local knowledge and expertise into risk assessment development to capture these regionally specific factors that might be overlooked in transferred methodologies.

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Implementation challenges related to institutional structures and governance arrangements represent additional barriers to effective risk assessment in North African contexts. Meddour-Sahar (2015) identified significant institutional challenges affecting wildfire management in Algeria, including fragmented responsibilities across multiple agencies, limited cross-sectoral coordination, and predominance of reactive rather than proactive management approaches. These institutional factors affect risk assessment implementation through constraints on data sharing, coordination difficulties between assessment and response functions, and limited integration of risk information into broader land management and development planning. Addressing these challenges requires attention to governance and institutional dimensions alongside technical aspects of risk assessment, potentially including formal coordination mechanisms, standardized information exchange protocols, and capacity development initiatives that span organizational boundaries rather than focusing on single agencies.

Despite these challenges, emerging opportunities exist for improving fire risk assessment in North African Mediterranean contexts. Salis et al. (2021) reviewed recent developments in forest fire risk mapping, highlighting how new technologies and methodological approaches could address some traditional constraints. Their analysis emphasized the potential of satellite remote sensing to overcome certain field data limitations, providing consistent, spatially comprehensive information about vegetation condition and change over time. Similarly, advances in modeling approaches that can function with limited calibration data offer possibilities for developing reasonably reliable risk assessments despite historical data gaps. The authors also noted increasing international cooperation on fire management across the Mediterranean basin, creating opportunities for knowledge transfer, technical support, and capacity development that could accelerate the development of more effective risk assessment systems in North African regions. These technological and cooperative developments suggest pathways toward more effective risk assessment frameworks tailored to North African Mediterranean contexts, though continued investment and adaptation efforts remain necessary to address persistent challenges.

2.6. Wildfire Management and Policy

2.6.1. Evolution of wildfire management approaches

Wildfire management approaches in Mediterranean regions have undergone significant evolution over recent decades, reflecting changing understanding of fire ecology, socioeconomic contexts, and environmental conditions. Pausas and Vallejo (1999) traced the historical development of fire management in European Mediterranean ecosystems, noting that traditional approaches dating back centuries incorporated sophisticated understanding of fire behavior and ecological effects. These traditional systems typically involved controlled burning to manage fuel loads, create landscape mosaics for agricultural and pastoral purposes, and maintain ecosystem services. However, the authors documented how these traditional practices were largely abandoned during the 19th and 20th centuries as rural depopulation occurred, agricultural modernization reduced

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traditional burning, and formal forest management institutions implemented fire exclusion policies based on the perception of fire as uniformly destructive.

Keeley et al. (2011) further elaborated on this historical trajectory, describing how early 20th century management emphasized complete fire suppression based on the perception of fire as an external disturbance to be eliminated rather than an integral ecological process. This suppression paradigm dominated Mediterranean fire management for much of the 20th century, with substantial investments in firefighting capabilities but limited attention to prevention, fuel management, or ecological considerations. The authors documented how this approach proved increasingly inadequate as fuel accumulation, climate change, and expanding wildland-urban interfaces created conditions conducive to larger and more severe fires that frequently exceeded suppression capabilities. These limitations drove gradual reconsideration of management philosophies, with growing recognition of the need for more balanced approaches that acknowledge fire's ecological role while protecting human communities and values at risk.

More recently, wildfire management has increasingly emphasized integrated, risk-based approaches that balance multiple objectives including ecosystem health, community safety, and resource protection. Moreira et al. (2020) examined wildfire management paradigms in Mediterranean-type regions, describing the gradual transition toward more comprehensive frameworks that address the full spectrum of risk factors and management options. Their analysis identified several key shifts in management philosophy, including greater emphasis on proactive fuel management rather than reactive suppression, increasing attention to spatial prioritization based on risk assessment, and growing recognition of fire's ecological role in many Mediterranean ecosystems. These conceptual advances reflect deeper understanding of Mediterranean fire ecology as well as practical recognition that suppression-centered approaches alone cannot address the complex challenges posed by changing fire regimes in the context of climate change, land use transformation, and evolving societal expectations.

The integration of traditional knowledge with modern scientific approaches represents an emerging direction in Mediterranean fire management evolution. Leone et al. (2009) examined human factors of fire occurrence in the Mediterranean, highlighting the potential value of traditional ecological knowledge for informing contemporary management. Their research documented how traditional Mediterranean cultures developed sophisticated understanding of fire behavior and effects through centuries of practical experience, creating management systems that regulated fuel loads while providing various ecosystem services. The authors suggested that while direct replication of historical practices may not be feasible in contemporary landscapes, the principles underlying traditional approaches—including strategic use of managed fire, spatial heterogeneity in fuel treatments, and integration of fire management with broader land use objectives—offer valuable insights for developing more sustainable contemporary practices that work with rather than against fundamental ecological processes.

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2.6.2. Prevention, preparedness, response, and recovery frameworks

Comprehensive wildfire management frameworks incorporate multiple components addressing different temporal phases of the fire management cycle. Tedim et al. (2018) examined challenges and impacts of extreme wildfire events, emphasizing the importance of integrated approaches that balance pre-fire prevention and mitigation with during-fire response and post-fire recovery. Their research demonstrated that these components are interdependent, with investments in prevention potentially reducing response requirements, while effective recovery approaches can lower future prevention needs through strategic rebuilding and ecosystem restoration. This integrated perspective highlights the importance of coordinated planning across all management phases rather than treating them as separate domains. The authors particularly emphasized the limitations of response-focused approaches for addressing extreme wildfire events, which often exceed suppression capabilities regardless of resource investments, suggesting the need for greater emphasis on prevention and mitigation activities that reduce landscape vulnerability before fires occur.

Prevention represents a fundamental component of effective wildfire management in Mediterranean contexts. Meddour-Sahar et al. (2013) analyzed forest fire causes and motivations in northern Algeria, emphasizing the importance of addressing human-related ignition sources through targeted prevention programs. Their research using the Delphi method with fire management experts identified several priority prevention approaches, including public education campaigns, agricultural burning regulations, enhanced enforcement near high-risk areas, and strategic fuel management in critical locations. The authors particularly highlighted the importance of addressing underlying socioeconomic factors that influence fire use and management behaviors, suggesting that sustainable prevention requires addressing root causes of human-caused ignitions rather than focusing solely on technical or regulatory interventions. This perspective aligns with findings from Leone et al. (2009), who documented the complex social, economic, and cultural factors influencing human-fire relationships in Mediterranean communities.

Fuel management represents an essential prevention component that directly addresses landscape flammability. Moreira et al. (2020) advocated for paradigm shifts in Mediterranean wildfire management, emphasizing the critical importance of strategic fuel treatments for reducing fire intensity and spread potential. Their analysis reviewed various fuel management approaches, including prescribed burning, mechanical thinning, targeted grazing, and creation of fuel breaks in strategic locations. The authors emphasized that effective fuel management requires careful prioritization based on risk assessment, noting that treating entire landscapes is neither feasible nor desirable. Instead, they advocated for spatially optimized treatments focused on critical areas such as wildland-urban interfaces, evacuation corridors, strategic ridgelines, and areas of high ecological value. This targeted approach recognizes the reality of limited resources while maximizing the effectiveness of fuel management investments through strategic placement and maintenance.

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Preparedness encompasses the planning, training, and resource allocation necessary to effectively respond to fire events when they occur. Tedim et al. (2018) highlighted several key preparedness components, including risk assessment and early warning systems, pre-positioned suppression resources, training programs for fire management personnel, evacuation planning for vulnerable communities, and coordination mechanisms among different agencies and jurisdictions. The authors emphasized that effective preparedness requires not only technical and operational readiness but also social and institutional preparation, including clear communication protocols, established decision-making structures, and mechanisms for coordinating across organizational boundaries. These social and institutional dimensions are particularly important for addressing extreme wildfire events that typically involve multiple organizations and require complex, coordinated responses under challenging conditions.

Response capabilities remain essential despite increased emphasis on prevention and preparedness, particularly for protecting communities and critical infrastructure. Fernandes et al. (2016) analyzed characteristics and controls of extremely large wildfires in the western

Mediterranean Basin, examining the relationships between suppression strategies and fire outcomes. Their research documented how initial attack speed, resource deployment patterns, and tactical approaches influence fire containment success, with particular emphasis on the importance of rapid, coordinated response to emerging fire events before they exceed suppression thresholds. However, the authors also noted the limitations of suppression for controlling fires under extreme weather conditions, suggesting that response strategies should recognize these constraints and prioritize life safety and structure protection when fires cannot be directly contained. This perspective aligns with Moreira et al. (2020), who advocated for response approaches that strategically allocate limited resources based on protection priorities rather than attempting to control all fires under all conditions.

Recovery following fire events has received increasing attention as an integral component of the management cycle. Tessler et al. (2016) studied vegetation recovery following recurrent fires in the Eastern Mediterranean ecosystem of Mount Carmel, emphasizing the importance of post-fire management for promoting ecosystem resilience and restoration. Their research documented various recovery approaches including soil stabilization measures, strategic revegetation efforts, management of natural regeneration processes, and monitoring programs to track ecosystem responses. The authors particularly highlighted the importance of understanding fire severity patterns when designing recovery interventions, as different severity levels create distinct post-fire environments requiring different management approaches. Beyond ecological dimensions, BentoGonçalves and Vieira (2020) emphasized the social and infrastructural aspects of post-fire recovery, including rebuilding with fire-resistant materials, improving evacuation routes and water systems, and implementing enhanced building codes and vegetation management requirements in reconstruction efforts. These approaches use the recovery phase as an opportunity to reduce future vulnerability through adaptive rebuilding that addresses identified weaknesses revealed during fire events.

2.6.3. Algerian institutional framework for wildfire management

Algeria's institutional framework for wildfire management involves multiple governmental agencies with distinct but overlapping responsibilities. Meddour-Sahar (2015) examined wildfire problems and challenges in Algeria, describing the complex institutional landscape involving forestry departments, civil protection services, local government authorities, and various other entities. Their analysis noted that primary responsibility for forest fire management officially resides with the Directorate General of Forests (DGF) within the Ministry of Agriculture, which oversees prevention activities, detection systems, and initial response in forested areas. However, operational firefighting authority transitions to Civil Protection services (within the Ministry of Interior) for larger incidents, creating potential coordination challenges during rapidly evolving fire situations. Additional entities involved in various aspects of fire management include local communes responsible for municipal fire prevention, meteorological services providing fire weather forecasts, and military units that may be mobilized during extreme fire events. This complex institutional arrangement creates significant coordination requirements that have not always been effectively addressed through formal mechanisms.

The legal and regulatory framework governing wildfire management in Algeria has developed over several decades, with important recent updates addressing emerging challenges. Meddour-Sahar et al. (2013) analyzed forest fire causes in northern Algeria, referencing the legal context for fire management activities. Their research noted that the fundamental Forest Law of 1984 (amended in 2012) establishes basic protection measures including activity restrictions during high fire danger periods, requirements for preventive clearing around infrastructure, and provisions for postfire restoration. Additionally, various regulations specify institutional responsibilities and operational procedures for different aspects of fire management. However, the authors noted significant gaps between formal legal requirements and actual implementation, with limited enforcement of many provisions due to resource constraints, coordination difficulties, and competing priorities. These implementation challenges highlight the importance of considering both formal institutional structures and operational realities when assessing the effectiveness of wildfire governance arrangements.

Coordination mechanisms represent a critical but challenging aspect of Algeria's institutional framework. Meddour-Sahar (2015) highlighted how wildfire management responsibilities are distributed across administrative levels, with national agencies establishing overall policy directions and providing technical guidance, while implementation occurs primarily through province (provincial) and commune (local) level authorities. Their analysis identified formal coordination structures including provincial fire management committees that bring together representatives from forestry departments, civil protection services, local governments, and other stakeholders to develop annual prevention plans and coordinate response activities during fire seasons. However, they noted that these mechanisms often face operational challenges including unclear authority relationships, inadequate information sharing, and resource allocation conflicts. The effectiveness of coordination efforts varies considerably across different regions, reflecting

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differences in leadership commitment, institutional capacity, and historical working relationships that influence how formal coordination structures function in practice.

Funding and resource allocation within Algeria's institutional framework present ongoing challenges for effective fire management. Meddour-Sahar (2015) noted significant disparities between management needs and available resources, with chronic underfunding affecting multiple aspects of the management system. Their research documented how budget constraints affect various components of fire management, from limited prevention activities and inadequate maintenance of firefighting equipment to insufficient personnel during peak fire periods. These resource limitations are particularly pronounced at local levels where implementation occurs, creating capacity gaps that compromise management effectiveness despite relatively robust policy frameworks at national levels. The author emphasized that resource allocation challenges reflect both absolute funding limitations and strategic prioritization decisions that have historically emphasized response capabilities over prevention and preparedness, creating imbalanced investment patterns that may not optimize overall system effectiveness given the changing nature of fire challenges facing the region.

2.6.4. Current management strategies in the province of Tlemcen

Wildfire management in the Province of Tlemcen incorporates various strategies addressing different aspects of fire risk, though significant challenges remain in implementing comprehensive approaches. Belgherbi and Benabdeli (2021) conducted structural analysis of burnt areas by forest fires in Tlemcen National Park, providing context on current management efforts in the region. Their research described how the Tlemcen forestry authorities implement annual fire management plans that emphasize prevention infrastructure including firebreaks and water points, surveillance systems during high-risk periods, public awareness campaigns in rural communities, and coordination with Civil Protection for suppression activities. These efforts focus particularly on high-risk zones identified through spatial assessment, though resource limitations constrain implementation across the extensive forested areas within the province. The authors noted that current management approaches still emphasize protection of commercial timber resources and infrastructure rather than integrated ecosystem management, creating potential gaps in addressing broader landscape resilience and ecological considerations.

Fuel management strategies in Tlemcen reflect both traditional approaches and emerging practices. Belgherbi and Benabdeli (2021) documented various fuel treatment methods implemented in the region, including strategic firebreak networks, selective thinning in high-risk forest stands, and clearing around key infrastructure and settlements. Their analysis indicated that approximately 5% of the forested area receives some form of fuel management treatment annually, primarily focused on creating and maintaining firebreaks along ridgelines, roads, and around settlements. These treatments aim to compartmentalize the landscape to limit potential fire spread while providing safe operational zones for firefighting activities. However, the authors noted significant limitations in current implementation, including insufficient maintenance of existing fuel breaks, limited

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application of ecological principles in treatment design, and minimal use of prescribed fire despite its potential effectiveness for managing accumulated fuels in Mediterranean pine forests.

Detection and monitoring systems represent important components of current management strategies in Tlemcen. Meddour-Sahar and Derridj (2012) analyzed forest fires in Algeria, describing the fire detection infrastructure operating in the Tlemcen region. Their research noted a network of fire lookout towers at strategic locations providing visual surveillance during fire seasons, supplemented by ground patrols in high-risk areas and community reporting mechanisms. These traditional detection approaches have been partially modernized through the addition of mobile communication capabilities that enable faster reporting and verification of detected ignitions. However, the authors identified significant gaps in detection coverage, particularly in more remote areas, and noted the limited integration of newer technologies such as automated camera systems or satellite-based hotspot detection that could enhance coverage across the extensive and often rugged terrain.

Suppression resources and strategies in Tlemcen reflect the broader Algerian approach emphasizing rapid initial attack when possible. Meddour-Sahar (2015) examined wildfire problems and challenges in Algeria, referencing the suppression capabilities available in the Tlemcen region. Their analysis indicated that firefighting resources are distributed across the province based on historical fire patterns and access considerations, with primary responsibility divided between forestry services (for initial attack in forested areas) and Civil Protection units (for larger incidents and structure protection). Suppression strategies emphasize direct attack methods when fire behavior permits, transitioning to point protection of critical infrastructure and communities during more extreme fire events that exceed containment capabilities. The author noted significant challenges related to limited water availability in many areas, difficult access in rugged terrain, and coordination issues between different response agencies that sometimes create operational inefficiencies during complex incidents involving multiple jurisdictions.

Community engagement represents an increasingly important but still developing aspect of Tlemcen's fire management approach. Leone et al. (2009) examined human factors of fire occurrence in Mediterranean regions, discussing community involvement initiatives in contexts similar to Tlemcen. Their research framework provides insights relevant to community engagement approaches in the region, which currently include educational programs targeting rural communities and schools, seasonal awareness campaigns, and limited collaborative management efforts involving local stakeholders. However, these initiatives remain relatively restricted in scope and integration with formal management structures, representing an area for potential enhancement through more structured engagement frameworks and meaningful participation in planning and decision-making processes. The authors emphasized that effective community engagement requires addressing underlying socioeconomic factors that influence fire risk behaviors rather than focusing solely on awareness and regulation, suggesting the need for more comprehensive approaches that connect fire management with broader rural development and livelihood considerations.

2.6.5. Integrating Climate Change Adaptation into Wildfire Management

Climate change presents fundamental challenges for wildfire management in Mediterranean regions, necessitating adaptation strategies that address emerging conditions and risk factors. Turco et al. (2014) reviewed climate change and wildfires in the Mediterranean region, emphasizing the importance of developing management approaches explicitly designed for changing climate conditions rather than relying on historical patterns and practices. Their research highlighted several key adaptation principles, including managing for resilience rather than stability, expecting and planning for surprises and threshold effects, implementing adaptive management frameworks that incorporate learning processes, and developing strategies robust across multiple potential future scenarios given inherent climate projection uncertainties. These principles represent significant departures from traditional management approaches that often assumed relatively stable environmental conditions and predictable fire behavior patterns, requiring fundamental reconsideration of management objectives, strategies, and performance metrics.

Risk assessment approaches represent a critical foundation for climate-adapted fire management. Salis et al. (2021) reviewed recent developments in forest fire risk mapping in Mediterranean areas, emphasizing the importance of forward-looking risk assessment that incorporates climate projections rather than relying solely on historical patterns. Their research demonstrated how advanced modeling techniques can integrate climate change scenarios with other risk factors to project future fire potential, enabling more proactive management planning that addresses emerging conditions rather than responding to past events. The authors particularly highlighted the value of scenario-based approaches that consider multiple possible future conditions rather than single deterministic projections, acknowledging the substantial uncertainties inherent in climate change projections while still providing actionable information for adaptation planning and implementation. These climate-informed risk assessments provide essential foundations for prioritizing adaptation investments and developing management strategies aligned with projected future conditions.

Fuel management strategies require reconsideration and adaptation in the context of changing climate conditions. Moreira et al. (2020) advocated for paradigm shifts in Mediterranean wildfire management, highlighting implications for vegetation management approaches under climate change. Their research suggested that traditional fuel reduction methods designed for historical fire regimes may prove inadequate under more extreme climate conditions, requiring modifications such as wider treatment areas, different spatial configurations to disrupt fire spread under stronger winds, and adjusted maintenance schedules to address faster fuel recovery in warmer conditions. The authors particularly emphasized the importance of strategic prioritization given that treating entire landscapes remains infeasible, suggesting risk-based approaches that focus limited resources on areas of highest value and vulnerability. Additionally, they noted the importance of species selection in restoration and reforestation efforts, emphasizing drought

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tolerant, fire-adapted species better suited to projected future conditions over commercial timber species that may face increasing climate stress and fire vulnerability.

Community preparedness and engagement represent increasingly important components of climate-adapted fire management. Bento-Gonçalves and Vieira (2020) examined key concepts and evaluation methodologies for wildfires in wildland-urban interface areas, emphasizing the need for enhanced community adaptation measures under changing climate and fire regimes. Their research highlighted approaches such as defensible space programs designed for more extreme fire conditions, improved building standards for increased fire resistance, community evacuation planning for larger and faster-moving fires, and collaborative risk governance systems that engage diverse stakeholders in developing locally appropriate adaptation strategies. The authors particularly emphasized the importance of social learning processes that build adaptive capacity at community levels, enabling more effective response to novel fire conditions that may exceed historical experience. These community-focused approaches complement landscape-scale management efforts while addressing the specific vulnerabilities of human communities and infrastructure in fire-prone areas.

Institutional adaptation represents an essential but challenging aspect of climate-adapted fire management. Moreira et al. (2020) emphasized that addressing changing fire regimes under climate change requires not only technical and operational adaptations but also fundamental reconsideration of governance arrangements, policy frameworks, and institutional structures. Their analysis identified several institutional barriers to effective adaptation, including fragmented responsibilities across multiple agencies, short-term planning horizons that contrast with long-term climate change processes, and management cultures resistant to substantial paradigm shifts. Overcoming these barriers requires deliberate attention to institutional dimensions of adaptation, potentially including revised legal and regulatory frameworks, new coordination mechanisms that facilitate integrated approaches across sectors and jurisdictions, and investment in building technical and professional capacity for addressing novel fire management challenges. The authors particularly highlighted the value of boundary organizations that can bridge science-policy divides, translating emerging research into actionable management approaches while ensuring that scientific efforts address practical management needs related to climate adaptation.

2.7. Research Gaps and Opportunities

Despite significant advances in wildfire science across the Mediterranean Basin, substantial knowledge gaps remain, particularly regarding North African fire regimes. These include limited systematic research on fire ecology in North African contexts, methodological challenges in wildfire risk assessment (especially in data-limited regions), insufficient integration of human dimensions into wildfire research, and persistent gaps between scientific knowledge and management implementation. Meddour-Sahar (2015) highlighted the scarcity of comprehensive fire history reconstructions and insufficient documentation of fire effects on regional biodiversity in North Africa, while Chuvieco et al. (2014) identified difficulties in combining factors operating

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at different spatial and temporal scales into coherent analytical frameworks. Additionally, despite widespread recognition of human influence on wildfire activity, the systematic examination of human ignition patterns and behaviors remains underdeveloped (Meddour-Sahar et al., 2013), and the implementation of scientific understanding into management practices continues to face barriers including institutional inertia, resource constraints, and coordination difficulties (Moreira et al., 2020).

2.7.1. Methodological challenges in wildfire risk assessment

Wildfire risk assessment in Mediterranean environments faces several methodological challenges that constrain the development and application of robust assessment frameworks. Chuvieco et al. (2014) identified difficulties in combining factors operating at different spatial and temporal scales into coherent analytical frameworks, while Salis et al. (2021) highlighted challenges in validating risk assessment approaches for future conditions without historical analogues. For North African contexts specifically, Meddour-Sahar (2015) emphasized data availability constraints that often necessitate simplification of assessment approaches, relying on limited subset variables rather than comprehensive data inputs. Additionally, Leone et al. (2009) documented the methodological challenges in quantifying complex human factors that significantly influence fire regimes but resist straightforward measurement and mapping. These methodological limitations constrain risk assessment capabilities for North African Mediterranean regions where integrated approaches are increasingly necessary for addressing complex fire management challenges.

2.7.2. Integration of human dimensions in wildfire research

Despite widespread recognition of human influence on wildfire activity, the integration of human dimensions into wildfire research remains underdeveloped, particularly in North African contexts. Meddour-Sahar et al. (2013) highlighted the limited research systematically examining human ignition patterns, motivations, and behaviors despite their dominant role in Mediterranean fire regimes. Leone et al. (2009) identified significant gaps in understanding socioeconomic, cultural, and institutional factors driving human-fire interactions in North Africa, creating knowledge deficits regarding a fundamental component of regional fire dynamics. Additionally, Oliveira et al. (2017) documented limited research on social vulnerability and community adaptation capacities in Mediterranean regions, constraining the development of socially appropriate risk reduction strategies. These knowledge limitations hinder the development of effective prevention programs and community engagement approaches that could address the predominantly human causes of fire ignition and spread in North African Mediterranean landscapes.

2.7.3. Positioning of the current research in addressing knowledge gaps

This research addresses several critical knowledge gaps regarding climate-vegetation-fire relationships in Mediterranean North Africa, with particular focus on the Tlemcen region of Algeria. By analyzing temporal trends in climate variables, vegetation indices, and fire activity, this study contributes to addressing fundamental data limitations identified by Meddour-Sahar (2015) regarding North African fire regimes. The research methodology leverages remote sensing

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technologies and geospatial analysis to overcome some traditional data constraints, aligning with approaches recommended by Chuvieco et al. (2014) for enhanced monitoring in data-limited regions. By examining correlations between climate variables, vegetation health indicators, and fire activity metrics, the research addresses knowledge gaps regarding climate-fire interactions in North African contexts identified by Turco et al. (2014). Methodologically, this research addresses challenges in wildfire risk assessment through its multi-temporal, multi-variable approach that integrates diverse data sources at compatible spatial scales. The application focus addresses aspects of the knowledge-to-action gap identified by Moreira et al. (2020) by developing spatially explicit information directly relevant to management planning in the Tlemcen region, potentially supporting improved prevention prioritization, preparedness planning, and adaptation strategies better aligned with projected climate change impacts on regional fire regimes.

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3.1 Location and Geographical Setting

The Tlemcen province is located in the northwestern part of Algeria, in the region commonly known as the Oranie (Figure 7). It occupies a strategic position near the Moroccan border in the western part of the Algerian Tell Atlas Mountains (Benabadi & Bouazza, 2000). The territory of Tlemcen extends across several distinct geographical zones, from the coastal plains in the north to the high steppe plateaus in the south, covering a total area of approximately 9,017 km² (Medjahdi et al., 2009).

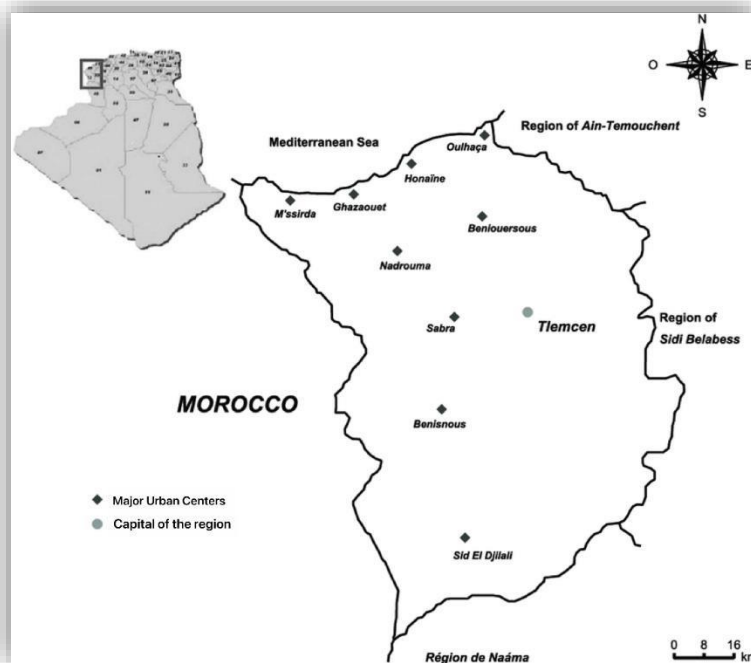


Figure 7: Geographic Location of the Tlemcen province in Northwestern Algeria

The topography of the region is characterized by significant elevation variations, with altitudes ranging from sea level in the northern coastal areas to over 1,800 meters at the highest points in the Tlemcen Mountains (Bouazza et al., 2001). This mountainous chain, which is part of the broader Tell Atlas system, forms the dominant topographical feature of the province and creates a natural barrier between the Mediterranean influences of the north and the more arid conditions of the southern plateaus.

Tlemcen National Park, established within this province, encompasses an area of approximately 8,225 hectares in the mountain zone, situated between 34°25' and 34°55' North latitude and 1°20' and 1°40' West longitude (Letreuch-Belarouci et al., 2009). The park area is characterized by rugged terrain with numerous peaks, valleys, and plateaus that create a diverse landscape with significant ecological heterogeneity. The park's boundaries were delineated to include

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representative forest ecosystems of the region, particularly the valuable cork oak formations that constitute an important natural heritage (Medjahdi et al., 2009).

From a geological perspective, the Tlemcen region presents diverse substrates that significantly influence soil development and vegetation distribution. The northern parts of the province are dominated by Jurassic limestone formations, while schists and sandstones are more prevalent in other areas (Bouazza et al., 2001). These geological variations, combined with the topographical diversity, have created a mosaic of soil types across the province, ranging from deep, fertile soils in the valleys to shallow, rocky soils on the steeper slopes.

The hydrographic network of Tlemcen is relatively well-developed, with several seasonal and permanent watercourses flowing through the territory. The main river systems include the Tafna basin, which drains much of the northern portions of the province, and various smaller watercourses that play important roles in supporting both natural ecosystems and agricultural activities (Benabadji & Bouazza, 2000). In addition to surface water resources, the region contains significant groundwater reserves associated with the limestone karst systems, although these have faced increasing pressure from human exploitation in recent decades.

This geographical diversity of the Tlemcen province, with its varied topography, geology, and hydrology, creates the foundation for the region's remarkable ecological characteristics. The transition zones between different geographical units are particularly significant, supporting distinctive ecotones with high biodiversity value (Bouazza et al., 2001). This natural heterogeneity has been historically shaped by both environmental factors and human influences, creating the complex landscape mosaic observed today across the province of Tlemcen.

3.2 Ecological Significance and Biodiversity

The province of Tlemcen possesses exceptional ecological significance due to its position at the intersection of different biogeographical zones, creating conditions for remarkable biodiversity. This region represents an important component of the Mediterranean biodiversity hotspot, harboring numerous endemic and rare species adapted to its diverse ecological conditions (Hasnaoui et al., 2011). The transitional nature of Tlemcen's ecosystems, positioned between Mediterranean, semi-arid, and mountain influences, contributes to its high species richness and ecological importance within the broader North African context.

The forestry resources of Tlemcen province are substantial, covering approximately 217,000 hectares (including reforestation areas), which represents 24% of the total area of the province. This makes the region one of the major forest zones in western Algeria, with significant timber resources, though still insufficient relative to the region's potential. According to the Conservation of Forests of Tlemcen (C.F.T., 2019), the forest distribution by species includes: Aleppo pine (*Pinus halepensis*) covering 83,000 hectares, holm oak (*Quercus ilex*) covering 82,000 hectares, cork oak (*Quercus suber*) occupying 48,000 hectares, thuya (*Tetraclinis articulata*) covering 16,500 hectares, juniper (*Juniperus sp.*) occupying 13,000 hectares, alfa grass (*Stipa tenacissima*)

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extending over 154,000 hectares, other species covering 17,000 hectares, and reforestation areas comprising 17,512 hectares. This distribution highlights the diversity of forest types in the region, each adapted to the specific environmental conditions of different ecological zones within the province.

Floristic diversity in the Tlemcen region is particularly noteworthy, with inventories documenting over 1,000 plant species distributed across its various ecosystems (Bouazza et al., 2001). The cork oak (*Quercus suber*) forests of the Tlemcen Mountains represent one of the most ecologically valuable formations, with Letreuch-Belarouci et al. (2009) identifying 67 species belonging to 31 different botanical families within these subéraies alone. These forests harbor numerous rare and endemic taxa, including medicinal plants of significant ethnobotanical importance, contributing to the region's status as a reservoir of plant genetic resources.

The diverse ecological conditions across the province have created multiple habitat types that support distinct biological communities. Hasnaoui et al. (2011) identified several key ecosystem types within the region, including humid and sub-humid forest formations in the northern mountains, pre-forest matorral communities in transitional zones, and steppe formations in the southern portions of the province. Each of these habitats supports specialized flora adapted to the specific environmental conditions, creating a complex mosaic of plant communities across the landscape. The inventory conducted by these researchers in the matorral ecosystems of Tlemcen revealed 62 species distributed across 29 botanical families, with Asteraceae, Lamiaceae, and Fabaceae being particularly well-represented.

From a conservation perspective, the region's forests merit special attention. Benabdeli (1996) highlighted the presence of several threatened and vulnerable tree species within Tlemcen's forests, including *Pistacia atlantica*, *Ceratonia siliqua*, and relict populations of *Tetraclinis articulata*. The author emphasized that these forest ecosystems provide critical habitat for numerous animal species as well, supporting a complex food web that includes various mammals, birds, reptiles, and invertebrates. The forest formations serve as ecological corridors that allow wildlife movement through the increasingly fragmented landscape, maintaining population connectivity and genetic exchange.

The health and integrity of these valuable ecosystems face significant threats, however. Bouhraoua and Villemant (2005) documented concerning declines in the health of cork oak stands in northwestern Algeria, including those in Tlemcen. Their research revealed that approximately 39% of the studied cork oak trees showed moderate to severe decline symptoms, attributed to various factors including drought stress, insect infestations, and inappropriate management practices. These findings highlight the vulnerability of even the region's most resilient forest ecosystems to combined anthropogenic and climatic pressures.

The matorral formations, which occupy significant portions of the province, represent an important component of Tlemcen's ecological heritage despite often being considered degraded versions of former forest ecosystems. Hasnaoui et al. (2011) emphasized the ecological value of

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these scrublands, which are characterized by drought-adapted shrub species such as *Chamaerops humilis*, *Pistacia lentiscus*, *Calicotome spinosa*, and various aromatic plants including *Thymus ciliatus* and *Rosmarinus officinalis*. These formations maintain substantial biodiversity and provide essential ecosystem services including soil protection, water regulation, and carbon sequestration despite their reduced structural complexity compared to intact forests.

The ecological significance of Tlemcen National Park, established within this broader ecological context, derives from its role in protecting representative examples of these diverse ecosystems. Letreuch-Belarouci et al. (2009) documented the park's importance as a conservation area for cork oak forests in particular, noting that it harbors some of the best-preserved stands remaining in the region. The park's protected status has helped maintain ecological processes and biodiversity that have been lost or degraded in surrounding unprotected areas, making it an essential reference ecosystem for understanding the natural dynamics of Mediterranean forest systems in northwestern Algeria.

3.3 Climate and Weather Patterns

The province of Tlemcen is characterized by a typical Mediterranean climate with distinct seasonal variations, though with significant local differences due to the region's complex topography and geographical position. Benabadji and Bouazza (2000) noted that the climate of the region follows a general Mediterranean pattern, with hot, dry summers and mild, relatively humid winters. However, this general pattern shows considerable variation across the province's diverse geographical zones, creating a mosaic of microclimatic conditions that significantly influence vegetation distribution and ecosystem dynamics.

The ombrothermic diagrams for Zenata and Maghnia weather stations (Figures 8 and 9) clearly illustrate the Mediterranean climatic regime characteristic of the Tlemcen region. As shown in Figure 8, Zenata station (2000-2019) recorded a mean annual temperature of 18.5°C and total annual precipitation of 345.4 mm. The diagram reveals a pronounced summer drought period (indicated by the red area) extending from approximately mid-May to early October, when temperatures peak (reaching 27.1°C in August) while precipitation drops dramatically (below 5 mm in July). The humidity period (blue area) occurs primarily during winter and early spring months, with maximum precipitation in November (over 70 mm) and January (approximately 50 mm).

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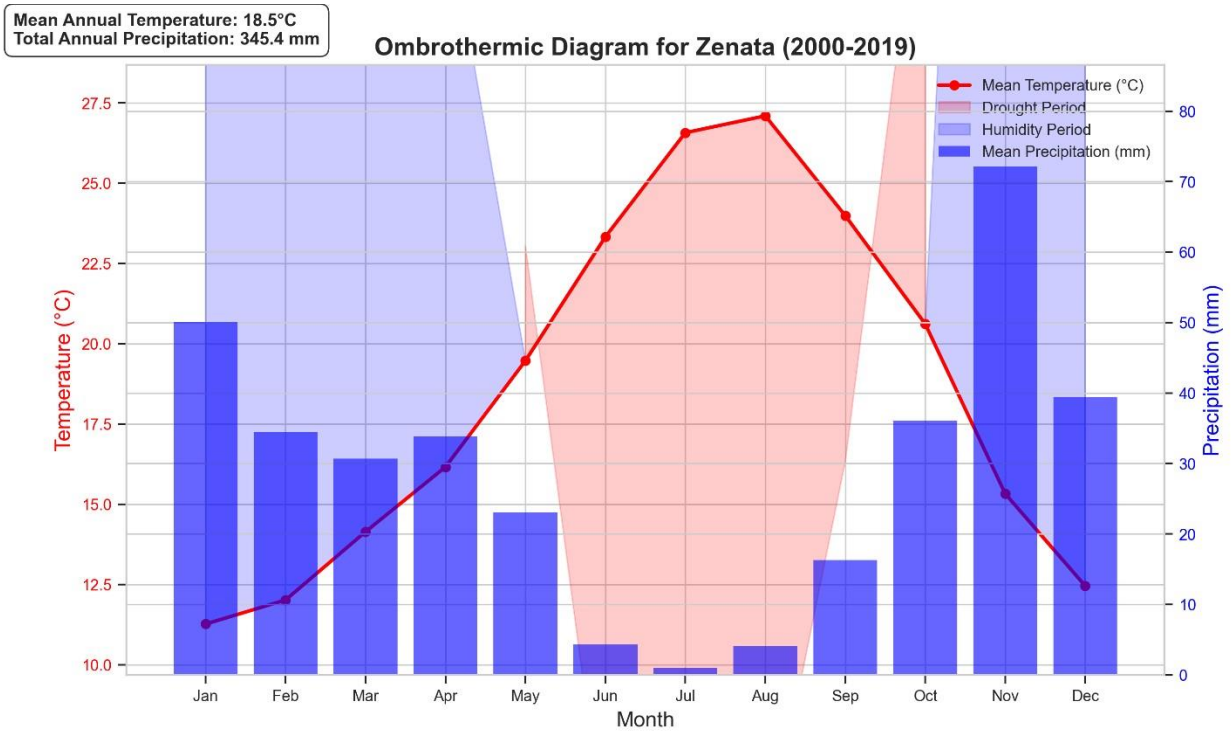


Figure 8: Ombrothermic Diagram for Zenata Weather Station (2000-2019)

The Maghnia station (Figure 9) exhibits a similar Mediterranean pattern but with some notable differences. With a mean annual temperature of 18.1°C and slightly higher annual precipitation of 372.9 mm, Maghnia's ombrothermic diagram shows a more pronounced March precipitation peak (approximately 75 mm) in addition to the November maximum (nearly 96 mm). The summer drought period is equally severe, with the dry season extending from late May to late September. Both stations demonstrate the characteristic rhythm of Mediterranean climates: a biological rest period during the summer due to water stress, despite high temperatures, and a principal growing season in spring and autumn when moderate temperatures coincide with adequate moisture availability.

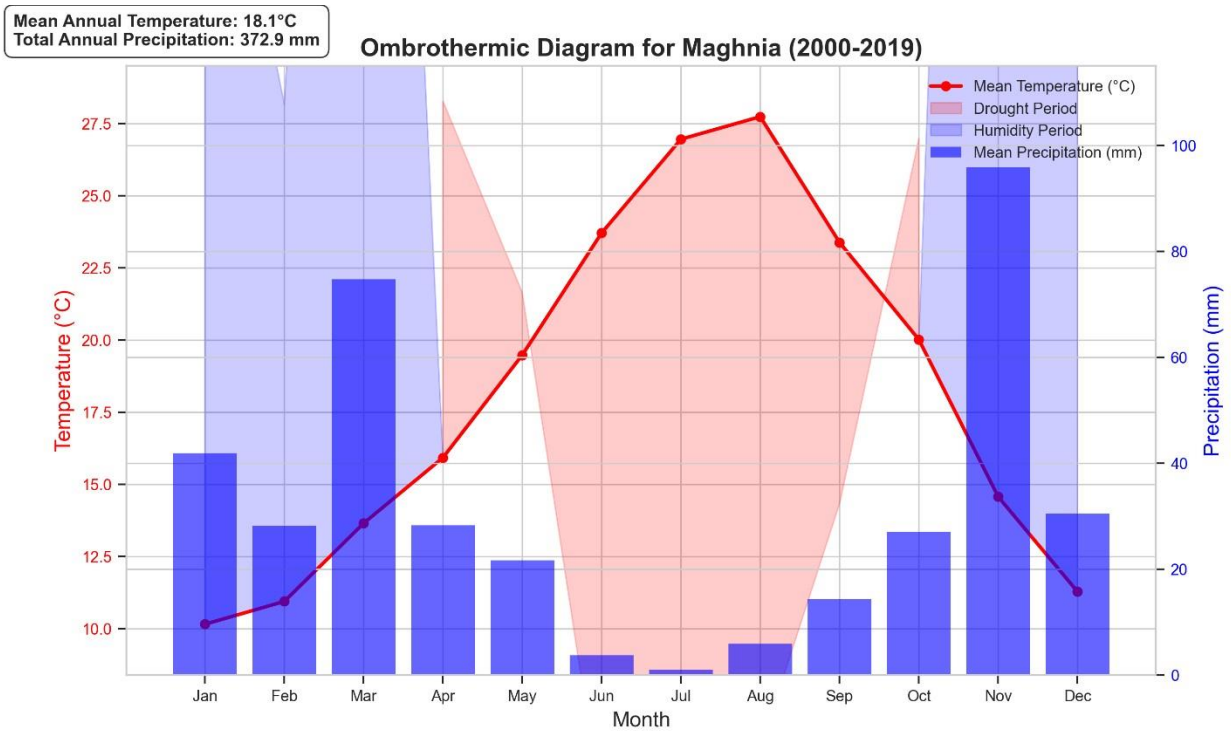


Figure 9: Ombrothermic Diagram for Maghnia Weather Station (2000-2019)

This precipitation gradient creates a transition from sub-humid conditions in the north to semi-arid and arid conditions in the south. The rainfall regime is characterized by high interannual variability, with significant fluctuations between wet and dry years that can substantially affect ecosystem functioning and agricultural productivity. Benabadji and Bouazza (2000) documented that approximately 80% of annual precipitation occurs during the winter and spring months (November to April), creating a pronounced dry season during summer that typically lasts 3-5 months depending on the specific location within the province.

The Tlemcen region has experienced notable climatic changes in recent decades that have affected ecological conditions and human activities. Benabadji and Bouazza (2001) documented a trend toward increasing aridity in the southwestern Oranie region, including parts of Tlemcen province, with declining precipitation and rising temperatures since the 1970s. Their analysis identified an approximate 20% reduction in average annual rainfall when comparing the periods 1913-1938 and 1970-1990, accompanied by a slight increase in mean annual temperatures. These changes have contributed to shifting bioclimatic zones, with semi-arid conditions expanding northward into previously sub-humid areas, creating new challenges for ecosystem management and conservation.

Wind patterns represent another important climatic factor affecting the Tlemcen region. Gaouar (1980) described the significance of both northern maritime winds that bring humidity from the

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Mediterranean and southern "sirocco" winds that occasionally bring hot, dry conditions from the Sahara. These wind patterns influence both temperature and moisture regimes, with the sirocco winds in particular associated with extreme fire weather conditions during summer months.

The topographical complexity of the Tlemcen region creates significant local variations in these broad climatic patterns. Aboura (2006) emphasized how elevation, aspect, and landform characteristics generate diverse microclimatic conditions across relatively small spatial scales. North-facing slopes typically experience cooler and moister conditions than south-facing slopes at equivalent elevations, creating distinctive vegetation patterns on opposing hillsides. These microclimatic variations contribute significantly to the region's ecological heterogeneity and biodiversity patterns.

The climate of the Tlemcen National Park area specifically reflects its mountainous position within this broader regional context. According to Aboura (2006), the park experiences relatively favorable moisture conditions compared to surrounding lower-elevation areas, with annual precipitation averaging 450-550 mm across most of its territory. This moderately humid climate, combined with cooler temperatures associated with higher elevations, creates conditions that have historically supported the development of forest ecosystems including valuable cork oak formations. However, even these more favorable climatic zones have experienced increasing aridity trends that threaten long-term ecosystem stability and resilience.

3.4 Vegetation Communities and Landscape Characteristics

The vegetation of Tlemcen province exhibits remarkable diversity reflecting the region's varied topography, climate, and soil conditions, as well as the long history of human influence on the landscape. Quézel and Santa (1962-1963) classified the vegetation of this region within the broader Mediterranean biogeographical context, noting that it contains elements from both the humid/subhumid Mediterranean formations to the north and the more xeric pre-Saharan formations to the south. This transitional position creates a complex vegetation mosaic with distinctive community types distributed along environmental gradients.

The forest formations of Tlemcen represent some of the most ecologically valuable vegetation communities in the region. According to Letreuch-Belarouci et al. (2009), the dominant forest types include cork oak (*Quercus suber*) forests in more humid zones, holm oak (*Quercus ilex*) formations at higher elevations and on northern slopes, and Aleppo pine (*Pinus halepensis*) stands in drier areas. These forest communities, though reduced from their historical extent, continue to provide important ecosystem services and harbor significant biodiversity. The authors documented that cork oak forests in the Tlemcen Mountains contain a rich understory with species such as *Arbutus unedo*, *Phillyrea angustifolia*, *Pistacia lentiscus*, and *Erica arborea*, creating a complex vertical structure that supports diverse faunal communities. These subéraies are particularly well developed in the national park area, where they represent the dominant forest type on siliceous substrates at elevations between 800 and 1,200 meters.

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Pre-forest and matorral communities occupy significant portions of the Tlemcen landscape, often representing degradation stages of former forest ecosystems. Hasnaoui (2008) conducted extensive studies of the chamaeropaie (dwarf palm) formations, documenting their distribution and ecological characteristics across the region. These formations are typically dominated by *Chamaerops humilis* associated with various sclerophyllous shrubs including *Pistacia lentiscus*, *Olea europaea* var. *sylvestris*, *Calicotome spinosa*, and *Phillyrea angustifolia*. The author noted that these matorral communities vary considerably in structure and composition depending on environmental conditions and degradation history, ranging from relatively tall (2-3m) and dense thickets in favorable sites to open, low-growing shrublands in more degraded or arid zones.

Steppe formations occur in the southern portions of the province where precipitation decreases below the threshold necessary to support forest development. Benabadji and Bouazza (1998) described these communities as being dominated by drought-adapted grasses such as *Stipa tenacissima* (alfa grass) and *Lygeum spartum* associated with various low shrubs and herbaceous species. These steppe ecosystems, while less structurally complex than forests, support significant biodiversity adapted to semi-arid conditions. The authors documented approximately 120 plant species in the steppe formations south of Tlemcen, many of which possess specialized adaptations to drought stress and poor soil conditions. These adaptations include reduced leaf surface area, waxy cuticles, deep root systems, and various physiological mechanisms for conserving water during prolonged dry periods.

Riparian vegetation communities form distinctive linear features within the broader landscape pattern. While not extensively described in the available references, Bouazza et al. (2001) mentioned that watercourses in the region support distinctive communities characterized by species such as *Nerium oleander*, *Tamarix africana*, *Fraxinus angustifolia*, and *Populus alba* in more permanent water courses. These riparian formations, though limited in extent, provide important ecological corridors within the increasingly fragmented landscape and support specialized biodiversity dependent on higher moisture availability than is found in surrounding upland areas.

The spatial distribution of these vegetation communities across the Tlemcen landscape follows distinctive patterns related to environmental gradients. Hasnaoui (2008) documented how elevation, aspect, substrate, and moisture availability interact to determine vegetation characteristics, with forests generally occurring in more mesic conditions at higher elevations and on north-facing slopes, while matorrals and steppes dominate drier sites and south-facing aspects. This basic pattern is further complicated by soil characteristics, with calciphilous communities on limestone substrates differing markedly from those on siliceous soils even under similar climatic conditions. The author particularly noted the distinctive vegetation communities that develop on the region's sandstone formations, which support specialized flora including several rare and endemic species.

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The current vegetation landscape of Tlemcen reflects not only these environmental factors but also a long history of human influence. Benabdeli (1983) emphasized that the present distribution and characteristics of vegetation communities cannot be understood without considering the cumulative effects of anthropogenic pressures over centuries. The author documented how activities such as forest clearing, livestock grazing, fuelwood collection, and agricultural expansion have progressively transformed the original vegetation cover, creating the current mosaic of relatively intact forests, degraded matorrals, and anthropogenic grasslands. Particularly notable is the author's observation that many current matorral formations represent degraded stages of former forest ecosystems, with soil erosion and changes in microclimate following deforestation often preventing natural forest regeneration even when direct human pressures are reduced.

Within Tlemcen National Park specifically, Letreuch-Belarouci et al. (2009) documented relatively better-preserved vegetation communities compared to surrounding unprotected areas, though noting that even these protected ecosystems show evidence of historical degradation. The park's vegetation is dominated by cork oak forests, which cover approximately 45% of its territory, with the remaining areas occupied by various matorral formations, holm oak stands, and limited representations of other community types. The authors noted that even within these protected forests, structural characteristics vary considerably depending on historical management and disturbance, with stand densities ranging from 120 to 750 trees per hectare and varying degrees of understory development related to past grazing intensity and fire history.

3.5 Fire History and Past Fire Events

The province of Tlemcen, like many Mediterranean regions, has experienced a long history of fire disturbance that has significantly shaped its landscape and ecosystems. According to Meddour-Sahar et al. (2013), fire has been a recurrent phenomenon in the region's forests and shrublands, with both natural and anthropogenic ignitions contributing to historical fire regimes. The authors noted that while lightning-caused fires occur occasionally, particularly during summer thunderstorms, the vast majority of contemporary fires in the region (over 95%) result from human activities, either accidental or deliberate.

Historical fire patterns in the broader region of northwestern Algeria have been partially reconstructed through various approaches. Slimani et al. (2014), using dendrochronological methods in Atlas cedar forests of northern Algeria, demonstrated that fire has been a consistent presence in Mediterranean forest ecosystems for centuries, though with varying frequency and intensity depending on climate fluctuations and human land use patterns. While their study focused on cedar forests in areas north of Tlemcen, it provides relevant context for understanding the long term role of fire in shaping the region's forest ecosystems. The authors identified several periods of increased fire activity over the past three centuries, often corresponding to periods of drought or significant changes in human land management practices.

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More specific to the Tlemcen region, Haddouche et al. (2011) conducted spatial analysis of forest fires in the province, documenting significant fire activity in recent decades. Their study, using a combination of historical records and remote sensing approaches, identified that approximately 21,000 hectares of forest and shrubland burned in Tlemcen between 1990 and 2010, representing nearly 14% of the province's total wooded area. The authors noted considerable spatial variability in fire occurrence, with certain zones experiencing repeated burning while others remained relatively fire-free during the study period. Areas with high fire frequencies were typically characterized by abundant flammable vegetation, proximity to human activities (particularly roads and settlements), and topographic features that facilitate fire spread such as steep slopes and ridge positions.

The seasonal pattern of fire occurrence in Tlemcen follows the typical Mediterranean regime, with Haddouche et al. (2011) documenting that approximately 80% of fires occur during the summer months (June-September), with peak activity in July and August when high temperatures and drought conditions coincide with maximum human presence in rural areas. This seasonal concentration of fire activity creates particular challenges for fire management, as multiple ignitions often occur during the most extreme fire weather conditions when suppression resources may be stretched thin across multiple incidents.

Within Tlemcen National Park specifically, fire has been a significant ecological factor affecting forest dynamics. Letreuch-Belarouci et al. (2010) studied the impact of fires on cork oak stands in the park, documenting that approximately 35% of the cork oak forests experienced at least one fire between 1980 and 2007. The authors noted varying fire effects depending on burn severity, with some areas experiencing high tree mortality (exceeding 75% in the most severely burned sites) while others showed primarily understory consumption with limited overstory damage. These differential fire effects created a mosaic of post-fire conditions across the landscape, ranging from relatively intact forests to severely degraded sites where conversion to shrubland occurred following high-severity burning.

The causes of fires in the Tlemcen region reflect complex socioeconomic and cultural factors. Meddour-Sahar et al. (2013), using the Delphi method with fire management experts, identified several primary human sources of fire ignition in northern Algeria, including agricultural burning, pastoral activities, discarded cigarettes, and in some cases, deliberate arson related to land use conflicts or illegal activities. The authors particularly highlighted the significance of agricultural practices as fire sources, with burning of crop residues frequently escaping control and spreading to adjacent natural vegetation. Additionally, they noted that changing rural demographics and land use patterns have altered traditional fire use practices, often increasing ignition risk while simultaneously reducing traditional landscape management activities that historically limited fire spread.

The ecological consequences of these fire patterns vary considerably depending on fire characteristics and ecosystem resilience. Letreuch-Belarouci et al. (2010) documented that cork

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oak forests, while possessing some adaptations to periodic fire such as thick insulating bark and resprouting capacity, can experience significant degradation when subjected to repeated burning at short intervals. The authors observed that sites experiencing multiple fires within a 10-15 year period often showed transitions from forest to shrubland, with failed regeneration of the tree canopy and expansion of fire-adapted shrub species. Conversely, areas experiencing only occasional, less severe fires typically maintained forest structure and composition, with the understory vegetation showing rapid post-fire recovery while the overstory trees survived due to their protective cork layer.

Recent fire trends in the region suggest changing patterns that may have important implications for future landscape dynamics. Haddouche et al. (2011) noted an apparent increase in both fire frequency and average fire size in Tlemcen during the period 2000-2010 compared to the previous decade, though acknowledging that this trend might partially reflect improved detection and reporting rather than actual changes in fire activity. The authors suggested that this potential increase could be related to a combination of factors including warming climate trends, vegetation changes creating more flammable landscape conditions, and evolving human activities that increase ignition probabilities in high-risk areas.

The devastating impact of these wildfires is clearly illustrated in Figure 10, which shows an aerial view of the extensive area burned during the 2015 wildfire in Tlemcen. This particular fire, one of the most severe in recent years, affected significant portions of forest ecosystems, primarily in areas dominated by pine and oak formations. The image reveals the mosaic burn pattern typical of Mediterranean wildfires, with varying severity levels creating a complex post-fire landscape. Such severe fires not only cause immediate ecological damage but can also trigger long-term vegetation changes and soil degradation when they occur in areas already suffering from drought stress and previous disturbances, as documented by Letreuch-Belarouci et al. (2010) in their studies of cork oak stands in the region.

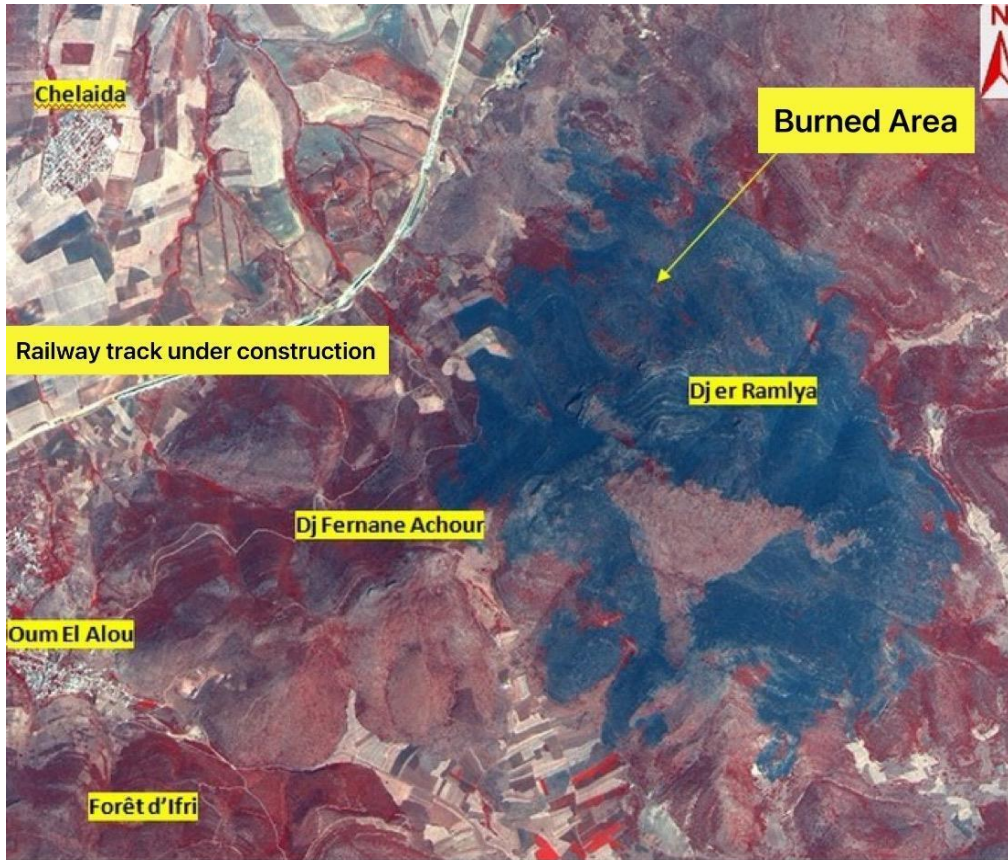


Figure 10: Aerial View of the 2015 Wildfire Area in Tlemcen National Park
(Source: A.S.A.L.)

3.6 Land Use and Management Practices

The landscape of Tlemcen province reflects a long history of human influence that has significantly shaped both natural ecosystems and agricultural lands. According to Benabdeli (1996), human settlement in the region dates back thousands of years, with successive civilizations leaving their mark on the landscape through various land use practices. The author noted that traditional land use systems in the region historically balanced resource extraction with conservation practices that maintained ecosystem functions, though this balance has been increasingly disrupted in recent decades by changing socioeconomic conditions and management approaches.

Pastoral activities represent one of the most significant land uses affecting natural ecosystems in Tlemcen. Benabdeli (1996) documented the importance of livestock grazing as both an economic activity and an ecological factor shaping vegetation structure and composition. The author's research on grazing impacts in the Télagh commune, which shares similar ecological characteristics with parts of Tlemcen, revealed that approximately 65% of forested and pre-forest areas experienced moderate to heavy grazing pressure. This grazing activity has contributed to

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significant changes in vegetation structure, particularly in the herbaceous and shrub layers, with preferential consumption of palatable species leading to gradual shifts in community composition toward less palatable, often spiny or toxic plants. The author particularly noted the expansion of unpalatable species such as *Asphodelus microcarpus*, *Urginea maritima*, and *Calicotome spinosa* in heavily grazed areas, creating persistent vegetation changes that may continue even if grazing pressure is subsequently reduced.

Forest management practices in the region have evolved considerably over time. LetreuchBelarouci et al. (2010) described how cork oak forests in Tlemcen, including those within the national park, have been managed primarily for cork production, with harvesting cycles typically occurring every 9-12 years. This management approach has influenced forest structure and regeneration patterns, with stand characteristics often reflecting past harvesting intensity and techniques. The authors noted that many cork oak stands show limited natural regeneration due to a combination of factors including grazing pressure, fire disturbance, and inappropriate harvesting practices that sometimes damage trees and reduce their vigor. These observations highlight the complex interactions between economic forest uses and ecological sustainability, with current conditions in many stands reflecting cumulative effects of management decisions over many decades.

Agricultural development represents another major land use in the Tlemcen region, with significant implications for natural ecosystem extent and condition. Bouazza and Benabadji (1998) documented how agricultural expansion has progressively converted natural vegetation to cropland, particularly in more level areas with deeper soils. The authors noted that while traditional agricultural systems often maintained elements of natural vegetation within a diverse landscape mosaic, more recent agricultural intensification has tended toward larger, more homogeneous crop fields with fewer natural elements. This transition has contributed to landscape fragmentation, with natural vegetation increasingly restricted to areas less suitable for agriculture due to steep slopes, shallow soils, or inaccessibility. The authors particularly emphasized the vulnerability of lowland riparian corridors to agricultural conversion, noting that these ecologically valuable areas have been disproportionately affected by land clearance due to their favorable soil and moisture conditions.

The interface between different land uses creates particular management challenges. Benabadji and Bouazza (2001) examined human impacts on forest ecosystems in Tlemcen, highlighting how urban expansion, infrastructure development, and recreational activities have created new pressures on forested areas. The authors documented increasing fragmentation of forest habitats by roads, power lines, and residential development, creating edge effects that alter ecological conditions and increase accessibility for various human activities. Of particular concern was their observation that forest-urban interfaces often experience increased fire ignition probability due to higher human presence combined with limited awareness of fire risk factors, creating hazardous conditions during the summer dry season when vegetation flammability is highest.

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Protected area management in Tlemcen National Park represents an attempt to balance conservation objectives with sustainable resource use. Letreuch-Belarouci et al. (2009) described how the park's management approach aims to preserve ecological values while accommodating certain traditional activities considered compatible with conservation goals. The authors noted that limited cork harvesting, controlled grazing, and collection of non-timber forest products are permitted within specified zones of the park, though with greater restrictions than in unprotected areas. This integrated approach recognizes the historical relationship between local communities and forest resources, seeking to maintain both cultural practices and ecological functioning rather than implementing strict exclusion policies. However, the authors also identified significant challenges in implementing these management intentions, with limited enforcement capacity and socioeconomic pressures often resulting in activities exceeding sustainable thresholds in some areas.

Land tenure changes have significantly influenced resource management approaches in the region. Benabdeli (1996) examined the impacts of land privatization on resource management in northern Algeria, noting how transitions from traditional collective management systems to private ownership have altered both access patterns and management incentives. The author documented that this transition has often led to more intensive resource extraction in the short term as new landowners seek to maximize immediate returns, sometimes at the expense of long-term sustainability. Particularly concerning were observations that privatization sometimes resulted in reduced investment in soil conservation measures and other long-term maintenance activities previously supported through collective action, creating increased vulnerability to degradation processes including erosion and productivity decline.

The cumulative effects of these various land use practices have created a highly heterogeneous landscape in Tlemcen province. Bestaoui (2001) described the current landscape as a complex mosaic of different vegetation types and land uses, ranging from relatively intact forest patches to heavily degraded areas, interspersed with agricultural lands of varying intensity, as illustrated in Figure 11. The author emphasized that this heterogeneity, while partly reflecting natural environmental variations, is largely the product of differential human impacts across the landscape, with current conditions in any given area reflecting its specific land use history. This complex pattern creates both challenges and opportunities for landscape-level management, requiring approaches that recognize the interconnections between different land units and use types while addressing the specific conditions and trajectories of individual landscape components.

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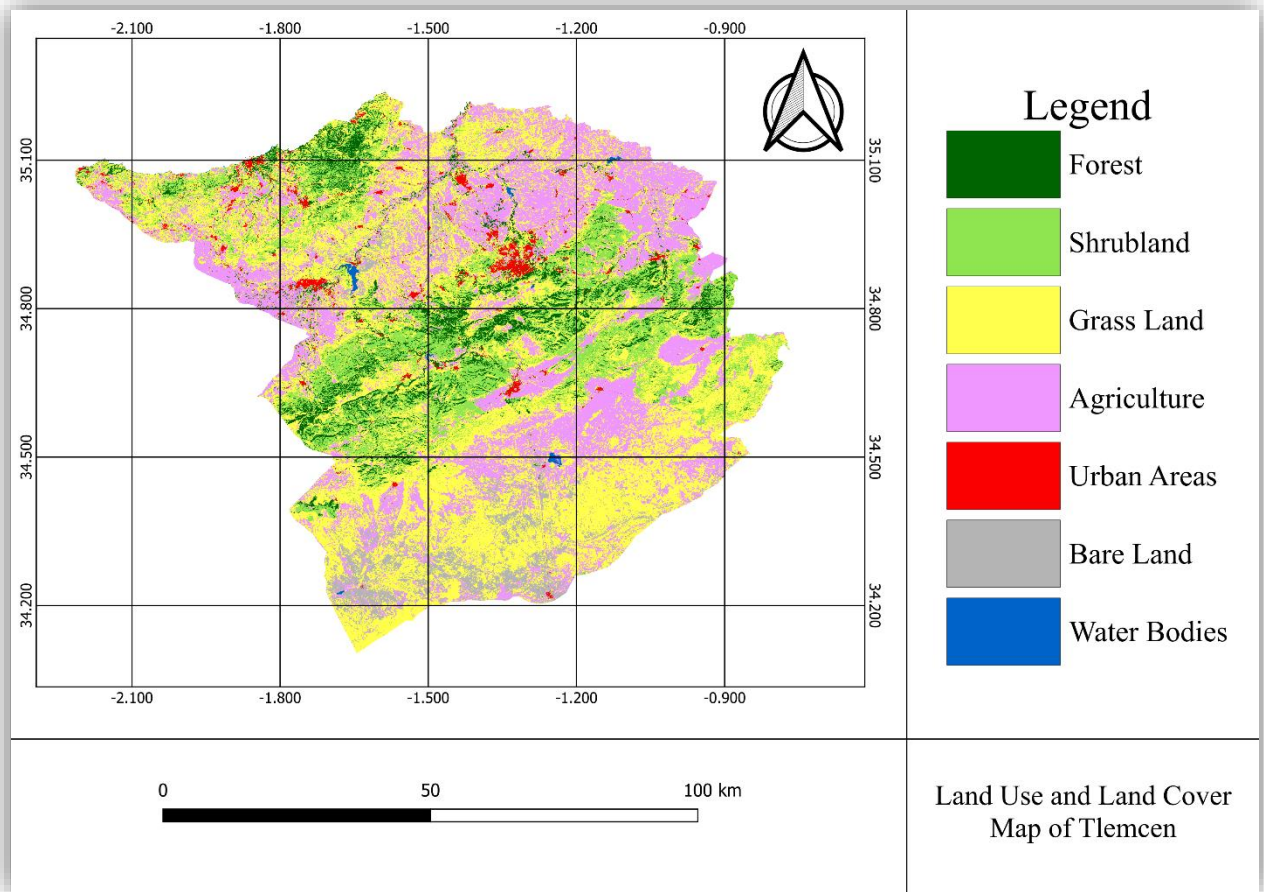


Figure 11: Land cover classification of Tlemcen Province based on MODIS Land Cover Type 1 (MCD12Q1)

4. METHODOLOGY

4.1 Study Area and Period

The research was conducted in Tlemcen Province, Algeria, focusing on the period from 2000 to 2019. This region was selected due to its Mediterranean climate characteristics and its vulnerability to climate-induced vegetation changes and wildfire events. The two-decade timespan provided sufficient temporal depth to detect meaningful trends in climate parameters, vegetation health, and fire activity while minimizing the influence of interannual variability.

The specific 2000-2019 timeframe was chosen after careful consideration of data availability and consistency constraints. For years prior to 2000, remote sensing data suffered from several limitations including lower spatial resolution, inconsistent sensor calibration, and significant gaps in coverage for the study area. The MODIS satellite platforms (Terra and Aqua), which provided the core datasets for this study, were launched in 1999 and 2002 respectively, making 2000 the earliest year with reliable MODIS-derived vegetation indices.

For years beyond 2019, three factors limited data inclusion: (1) the onset of the COVID-19 pandemic in early 2020, which disrupted field validation activities and introduced anomalous human pressure patterns on the landscape; (2) changes in the MODIS data processing algorithms that created consistency challenges with earlier data; and (3) the need to analyze complete 5-year periods, which would have required extending the study through 2024. Therefore, 2019 was selected as the terminal year for analysis, allowing for four complete 5-year periods (2000-2004, 2005-2009, 2010-2014, and 2015-2019) that enabled robust temporal comparisons.

4.2 Data Sources and Acquisition

4.2.1 Remote sensing data

Multiple satellite-derived datasets were utilized to characterize environmental variables:

Vegetation Indices: MODIS Vegetation Indices (MOD13Q1) were accessed through the Google Earth Engine (GEE) platform using the collection 'MODIS/006/MCD12Q1'. These data provided 16-day composites of both Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) at 250-meter spatial resolution throughout the study period.

Precipitation Data: CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) provided daily rainfall estimates at 0.05° resolution, which were acquired and processed through the GEE platform.

Temperature Data: MODIS Land Surface Temperature (LST) products were used to obtain temperature data, which were originally in Kelvin units and required conversion to Celsius for analysis.

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Burned Area Data: FireCCI burned area products with 250-meter resolution were utilized to quantify wildfire extent and frequency throughout the study period.

Land Cover Data: Two primary land cover datasets were incorporated:

- MODIS Land Cover Type 1 (MCD12Q1) data for 2001 (as 2000 data were unavailable) at 500-meter resolution
- ESA WorldCover data for 2019 at higher resolution (10 meters) to detect fine-scale landscape changes

4.2.2 Ancillary spatial data

The administrative boundary of Tlemcen Province was obtained as a shapefile and used to spatially constrain all analyses to the study area. This boundary file was imported into GEE as an asset using the path 'projects/ee-zakariblkh/assets/tlemcen_qgz'.

4.3 Google Earth Engine Processing

4.3.1 Platform overview

Google Earth Engine served as the primary platform for acquiring, processing, and analyzing the geospatial datasets. This cloud-based computing environment was selected for its ability to handle petabyte-scale satellite datasets and perform parallel processing of large-scale environmental analyses. The GEE platform provided critical advantages, including access to pre-processed datasets that reduced data calibration time, parallel computing capabilities that enabled rapid analysis of extensive regions, and reproducibility through shareable code scripts.

4.3.2 Data preprocessing workflow

The following preprocessing steps were implemented within GEE:

Temporal Filtering: All datasets were filtered to the 2000-2019 study period. For instances where 2000 data were unavailable (specifically for MODIS Land Cover), 2001 data were substituted using conditional logic.

Spatial Subsetting: All datasets were clipped to the Tlemcen Province boundary using the imported shapefile.

Quality Assurance: MODIS quality assurance (QA) bands were utilized to exclude pixels with cloud contamination or other quality issues that could introduce artifacts into the analysis.

Temporal Aggregation: To reduce seasonal noise and highlight decadal trends, data were aggregated into four 5-year periods: 2000-2004, 2005-2009, 2010-2014, and 2015-2019.

Data Export: Processed datasets were exported as CSV files to Google Drive for subsequent statistical analysis.

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4.4 Vegetation Indices Processing

4.4.1 NDVI and EVI calculation

Two complementary vegetation indices were utilized to assess vegetation health and density:

Normalized Difference Vegetation Index (NDVI) was calculated using the formula:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

Where NIR represents near-infrared reflectance and Red represents red reflectance. NDVI values range from -1 to 1, with healthy vegetation typically returning values above 0.3.

Enhanced Vegetation Index (EVI) was calculated using the formula:

$$\text{EVI} = G \times [(\text{NIR} - \text{Red}) / (\text{NIR} + C_1 \times \text{Red} - C_2 \times \text{Blue} + L)]$$

Where $G = 2.5$ (gain factor), $C_1 = 6$, $C_2 = 7.5$ (aerosol resistance coefficients), and $L = 1$ (soil adjustment factor). EVI was selected alongside NDVI due to its improved performance in regions with dense vegetation and aerosol pollution.

Rather than calculating these indices from raw spectral bands, the study utilized pre-computed NDVI and EVI products from MODIS MOD13Q1 to ensure consistency. Since MODIS vegetation indices are scaled by 10,000, a conversion factor was applied to obtain actual values:

$$\text{NDVI/EVI(actual)} = \text{NDVI/EVI(MODIS)} / 10000$$

4.4.2 Rationale for using both indices

The dual-index approach was employed for several reasons:

- NDVI provided continuity with previous studies and has been widely validated for monitoring vegetation health and biomass.
- EVI offered enhanced sensitivity in areas with dense vegetation and reduced susceptibility to atmospheric interference.
- The complementary nature of both indices provided a more robust assessment of vegetation stress related to climatic changes.

4.5 QGIS Processing

QGIS software was employed for several critical preprocessing steps that required desktop GIS capabilities:

4.5.1 Raster resampling

All raster datasets (NDVI, EVI, precipitation, and temperature) were resampled to a common 250-meter resolution using bilinear interpolation to ensure spatial alignment with the MODIS vegetation products. This step was necessary to enable pixel-by-pixel comparison between different environmental variables.

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4.5.2 Land cover classification

Both ESA WorldCover 2019 and MODIS 2000/2001 land cover datasets were used to reclassify and isolate fire-prone vegetation classes:

- Forest classes (MODIS classes 1-5; ESA class 10)
- Shrubland classes (MODIS classes 6-7; ESA class 20)

Non-relevant land cover types (urban areas, water bodies, and agricultural lands) were masked out to focus the analysis on ecosystems most susceptible to wildfire activity.

4.5.3 Zonal Statistics Calculation

For each 5-year period, zonal statistics were computed to extract summary metrics (mean, percentiles, and variability measures) for all environmental variables within the study area. This process enabled the quantification of spatial patterns and temporal trends across the province.

4.6 Data Rescaling and Unit Conversion

4.6.1 Temperature data processing

MODIS Land Surface Temperature (LST) values were originally provided in Kelvin units and required conversion to Celsius for interpretation. The following transformation was applied:

$$\text{Temp(Celsius)} = (\text{Temp(MODIS)} / 100 \times 0.02)$$

Where:

- Division by 100: Accounts for MODIS scaling factor
- Multiplication by 0.02: Converts scaled Kelvin to Celsius

4.6.2 Precipitation data processing

CHIRPS rainfall data (provided in mm/day) were summed annually and then averaged over 5-year periods to align with the temporal aggregation approach used for other variables.

4.7 Statistical Analysis

4.7.1 Data preparation and preprocessing

Prior to statistical analysis, several preprocessing steps were performed to ensure data consistency and compatibility:

Data Loading: The main climate and vegetation datasets were loaded from CSV files:

```
main_data=pd.read_csv("C:\\Users\\zakarya\\Downloads\\Analysis_Data_all2.csv")
fire_data=pd.read_csv("C:\\Users\\zakarya\\Downloads\\WildfireData_Tlemcen_2000_2019.csv")
```

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Data Rescaling: MODIS-derived indices required rescaling to obtain scientifically valid values:

```
main_data[ndvi_cols] /= 10000 # NDVI
main_data[evi_cols] /= 10000 # EVI
main_data[temp_cols] = (main_data[temp_cols] / 100) * 0.02 # Temperature
```

The temperature conversion incorporated three operations:

- Division by 100 to account for MODIS scaling factor
- Multiplication by 0.02 to convert scaled Kelvin to Celsius

Period Mapping: Yearly data were aggregated into 5-year periods:

```
fire_data['period'] = ((fire_data['Year'] - 2000) // 5) + 1
```

This created four distinct periods (1: 2000-2004, 2: 2005-2009, 3: 2010-2014, 4: 2015-2019).

Data Merging: Fire and climate datasets were merged based on the period field:

```
merged_data = pd.merge(main_data, fire_agg, on='period',
how='left')
```

4.7.2 Trend analysis with linear regression

Linear regression analysis was performed to identify directional trends in climate, vegetation, and fire variables over the four 5-year periods. A custom function was implemented:

```
def calculate_trend(x, y):
    slope, intercept, r_value, p_value, std_err = linregress(x,
y)
    return {'slope': slope, 'r2': r_value**2, 'p-value':
p_value}
```

The regression equation took the form:

$$y = \beta_0 + \beta_1x + \varepsilon$$

Where:

- y: Dependent variable (e.g., NDVI, temperature, fire counts)
- x: Independent variable (period: 1-4, representing 5-year intervals)
- β_1 : Slope indicating the rate of change per period
- β_0 : Intercept (baseline value at period 0)
- ε : Residual error

This analysis was applied to all key variables:

```
print("Precipitation Trend:",
calculate_trend(merged_data['period'],
merged_data['precip_precip_mean']))
```

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```
print("Temperature Trend:",
      calculate_trend(merged_data['period'],
                      merged_data['temp_temp_mean']))
print("NDVI Trend:", calculate_trend(merged_data['period'],
                                     merged_data['ndvi_ndvi_mean']))
print("EVI Trend:", calculate_trend(merged_data['period'],
                                     merged_data['evi_evi_mean']))
print("Fire Count Trend:",
      calculate_trend(merged_data['period'],
                      merged_data['FireCount_mean']))
print("Burned Area Trend:",
      calculate_trend(merged_data['period'],
                      merged_data['BurnedArea_mean']))
```

The `scipy.stats.linregress` function computed slope (β_1), intercept (β_0), Pearson's correlation coefficient (r), p-value, and standard error. The coefficient of determination (R^2) was calculated as r^2 to assess goodness of fit.

4.7.3 Correlation analysis

Both parametric (Pearson) and non-parametric (Spearman) correlation analyses were conducted to assess relationships between environmental variables:

```
corr_cols = [
    'precip_precip_mean', 'temp_temp_mean',
    'ndvi_ndvi_mean', 'evi_evi_mean',
    'FireCount_mean', 'BurnedArea_mean'
]
pearson_corr = merged_data[corr_cols].corr(method='pearson')
spearman_corr = merged_data[corr_cols].corr(method='spearman')
```

Pearson's Correlation Coefficient (r) was calculated using:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

Where:

- x_i and y_i are individual data points
- \bar{x} and \bar{y} are the means of the respective variables

Pearson's coefficient measures linear relationships between normally distributed variables, with values ranging from -1 (perfect inverse relationship) to +1 (perfect direct relationship).

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Spearman's Rank Correlation (ρ) was calculated using:

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

Where:

- d_i is the difference in ranks between paired observations
- n is the number of data pairs

This non-parametric method assesses monotonic relationships without assuming normal distribution.

Significant correlations ($|r| > 0.5$) were extracted and reported using a custom function:

```
def print_strong_correlations(corr_matrix, method_name):
    print(f"Strong {method_name} correlations (|r| > 0.5):")
    for i in range(len(corr_matrix.columns)):
        for j in range(i+1, len(corr_matrix.columns)):
            val = corr_matrix.iloc[i, j]
            if abs(val) > 0.5:
                print(f"{corr_matrix.columns[i]} vs
{corr_matrix.columns[j]}: {val:.2f}")
```

Correlation matrices were visualized as heatmaps using:

```
sns.heatmap(pearson_corr, annot=True, cmap='coolwarm',
fmt=".2f", mask=np.triu(np.ones_like(pearson_corr, dtype=bool)))
```

4.8 Land Use and Land Cover (LULC) Change Analysis

4.8.1 Data acquisition and preprocessing

MODIS Land Cover Type 1 (MCD12Q1) data with 500-meter resolution were used for LULC analysis, comparing 2001 (earliest available) and 2019 (latest available) classifications. The International Geosphere-Biosphere Programme (IGBP) classification schema provided standardized land cover categories that enabled consistent cross-year comparisons. This dataset was accessed through Google Earth Engine using the collection 'MODIS/006/MCD12Q1' and filtered for the respective years.

4.8.2 Area calculation and change detection

For each land cover class, total area was computed using GEE's `pixelArea()` function, which assigns each pixel a value equal to its area in square meters. Areas were summed within the study region and converted to hectares (ha). Change metrics included:

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Absolute Change: $\Delta\text{Area} = \text{Area}(2019) - \text{Area}(2001)$

Percent Change: $\%\Delta = (\Delta\text{Area} / \text{Area}(2001)) \times 100$

4.8.3 Integration with vegetation analysis

Land cover classes showing significant expansion or decline were cross-referenced with NDVI/EVI time series to identify vegetation health patterns. This integration revealed how land use transitions (such as forest loss and shrubland expansion) influenced vegetation decline and fire susceptibility in the region.

4.9 Rationale for Methodological Choices

Several key methodological decisions were made to enhance the robustness of the analysis:

5-Year Aggregation: Data were aggregated into 5-year periods to smooth interannual variability (including anomalous drought years) and highlight long-term trends that might otherwise be obscured by short-term fluctuations.

Dual Vegetation Indices: The combined use of NDVI and EVI provided complementary insights into vegetation stress, accounting for different sensitivities to vegetation structure, background soil effects, and atmospheric conditions.

High-Resolution ESA Data: The incorporation of fine-scale (10-meter) ESA WorldCover data for 2019 enabled the detection of landscape fragmentation patterns that emerged after 2010, which proved critical for accurate fire risk mapping.

Integrated Spatial-Statistical Approach: The combination of geospatial analysis (GEE, QGIS) with robust statistical methods created a comprehensive analytical framework capable of detecting, quantifying, and visualizing complex environmental relationships.

This methodology established a reproducible workflow that could serve as a template for similar studies in other semi-arid Mediterranean ecosystems facing comparable climate-vegetation-fire challenges.

5. RESULTS AND DISCUSSION

5.1 Climate Trends in Tlemcen Province (2000-2019)

5.1.1 Precipitation patterns

Precipitation in Tlemcen Province showed considerable variability during the study period (2000-2019), with an overall increasing trend that was not statistically significant (slope = 23.19 mm/period, $r^2 = 0.018$, p-value = 0.866). Average precipitation increased from approximately 1750 mm in 2000-2004 to 2200 mm in 2010-2014, followed by a sharp decline to about 1750 mm in 2015-2019 (Figure 12). This pattern reveals a non-linear trajectory in rainfall over the two decades, with the highest precipitation observed during the third period (2010-2014).

Interperiod variability, as indicated by the width of the interquartile range (25th to 75th percentiles), increased substantially during the later periods. This growing dispersion suggests greater rainfall extremes, with some areas experiencing intensified precipitation while others faced reduced rainfall within the same time periods. This pattern of increased variability aligns with climate change projections for Mediterranean regions, which predict more erratic precipitation regimes (IPCC, 2014).

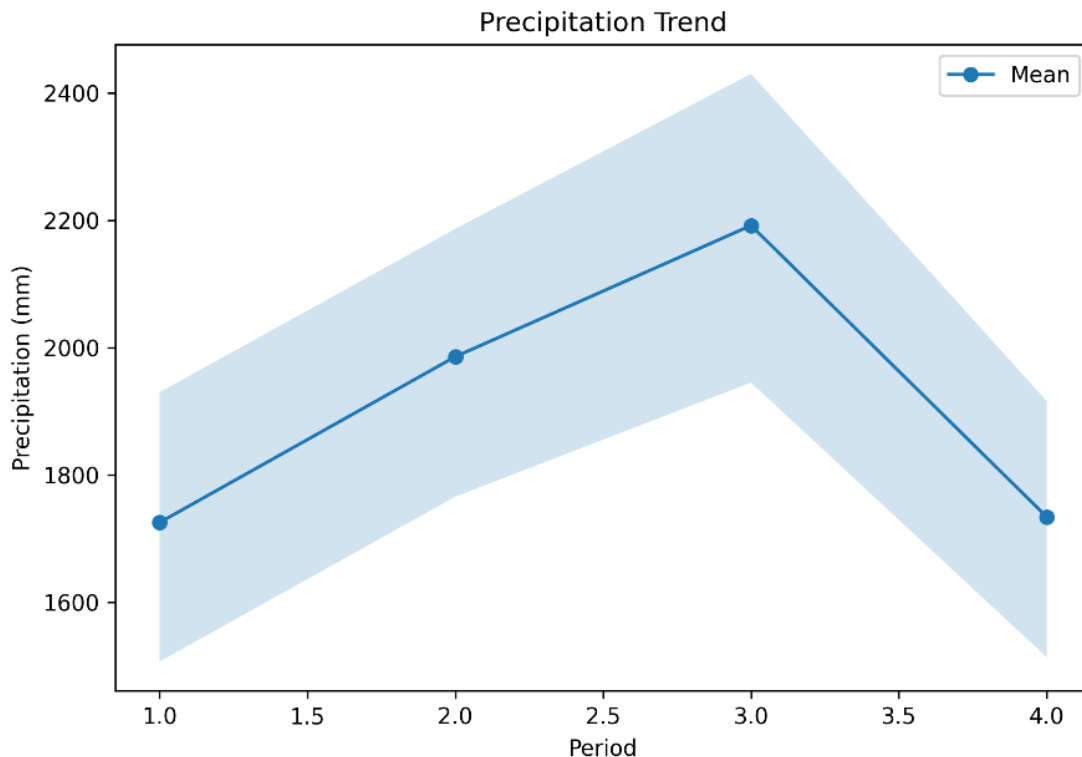


Figure 12: Average precipitation (mm) derived from CHIRPS data (2000-2019) for Tlemcen Province, Algeria

5.1.2 Temperature dynamics

Unlike precipitation, temperature exhibited a weak decreasing trend across the four periods (slope = $-0.006^{\circ}\text{C}/\text{period}$, $r^2 = 0.198$, $p\text{-value} = 0.554$). Mean temperature dropped slightly from 15.10°C in 2000-2004 to 15.06°C in 2005-2009 and reached its lowest point (15.05°C) in 2010-2014, before increasing again to 15.08°C in 2015-2019 (Figure 13). While the overall trend shows minimal cooling, the final period indicates a potential reversal toward warming.

The interquartile range for temperature expanded during the study period, particularly in the last period (2015-2019), indicating increased thermal variability across the province. This growing dispersion suggests that while average temperatures remained relatively stable, extremes became more pronounced, potentially increasing environmental stress on vegetation.

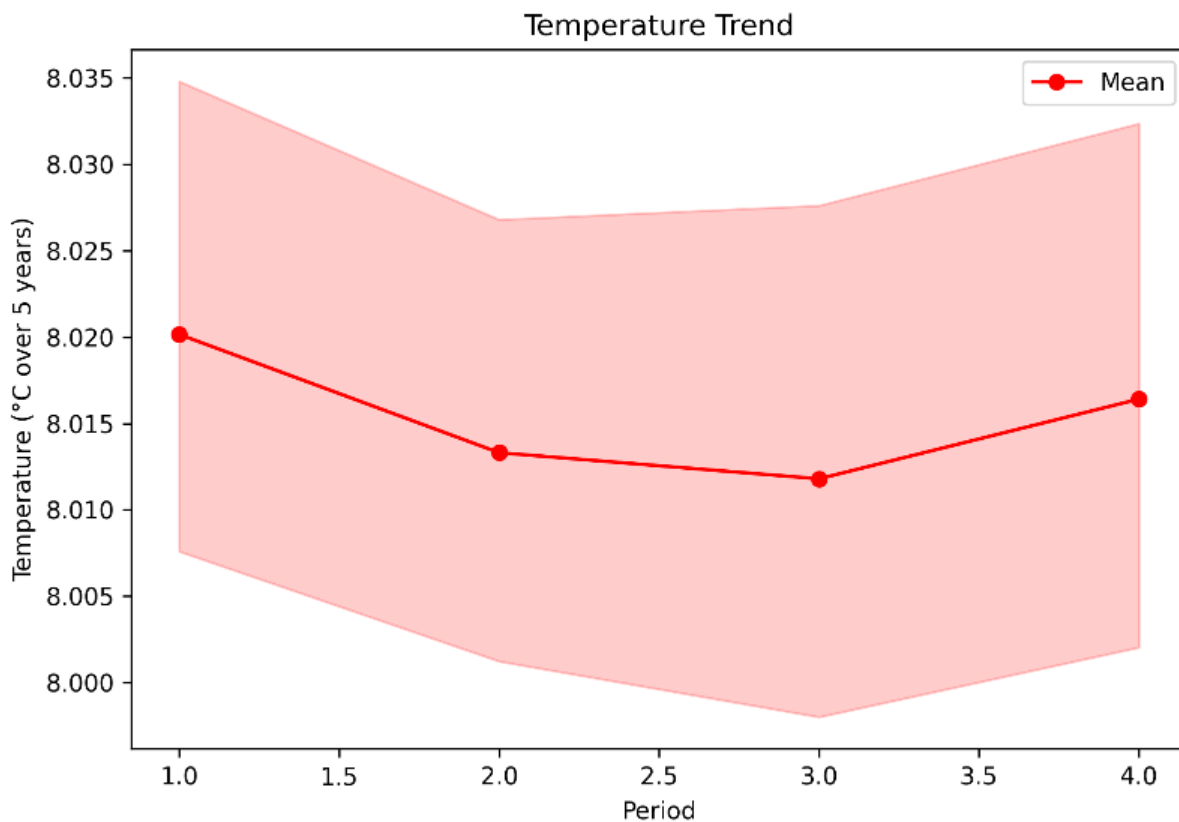


Figure 13: average Land Surface Temperature (LST) derived from MODIS LST products (2000-2019) for Tlemcen Province, Algeria

5.1.3 Climate interaction: precipitation-temperature relationship

A strong negative correlation was found between precipitation and temperature (Pearson's $r = -0.90$, Spearman's $\rho = -1.00$), indicating an inverse relationship where periods of higher rainfall corresponded with lower temperatures and vice versa. This strong anticorrelation is particularly evident in the 2010-2014 period, which experienced both peak precipitation and minimum temperature values.

This inverse relationship has important implications for environmental water balance and drought conditions. As temperature rises, increased evapotranspiration can exacerbate soil moisture deficits even when precipitation levels remain unchanged, potentially increasing vegetation stress and fire susceptibility.

5.2 Vegetation Health Dynamics

5.2.1 NDVI trends

Normalized Difference Vegetation Index (NDVI) values, which reflect vegetation greenness and health, showed minimal change over the study period (slope = 0.0009/period, $r^2 = 0.619$, p-value = 0.213). Mean NDVI values ranged from 0.287 in 2000-2004 to 0.308 in 2010-2014, followed by a slight decrease to 0.302 in 2015-2019 (Figure 14). While the overall trend was slightly positive, it was not statistically significant.

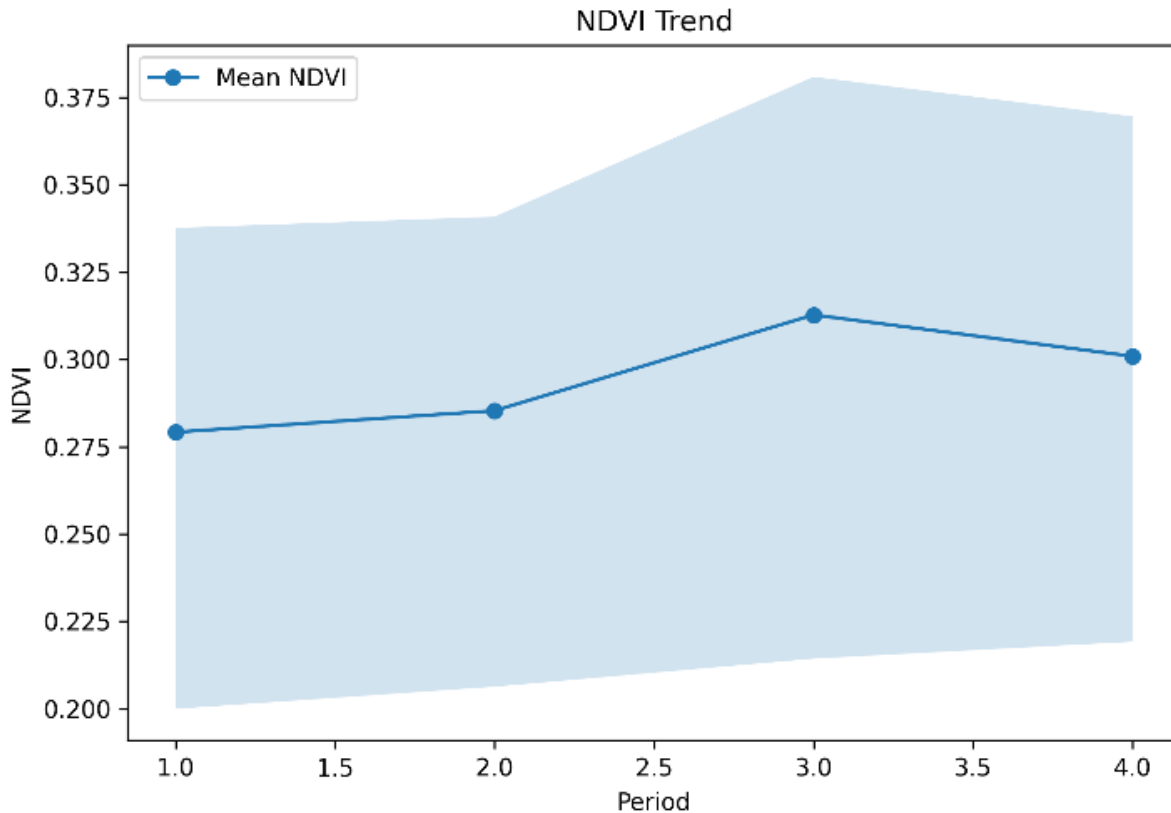


Figure 14: Normalized Difference Vegetation Index (NDVI) evolution derived from MODIS MOD13Q1 (2000-2019) for Tlemcen Province, Algeria.

The spatial distribution of NDVI values (as visualized in Figure 15) shows that vegetation health was highest in the Tlemcen and Trara mountains, particularly in areas dominated by Mediterranean forest. The central and southern regions, characterized by shrublands and steppes, consistently displayed lower NDVI values.

CHAPTER 5: RESULTS AND DISCUSSION

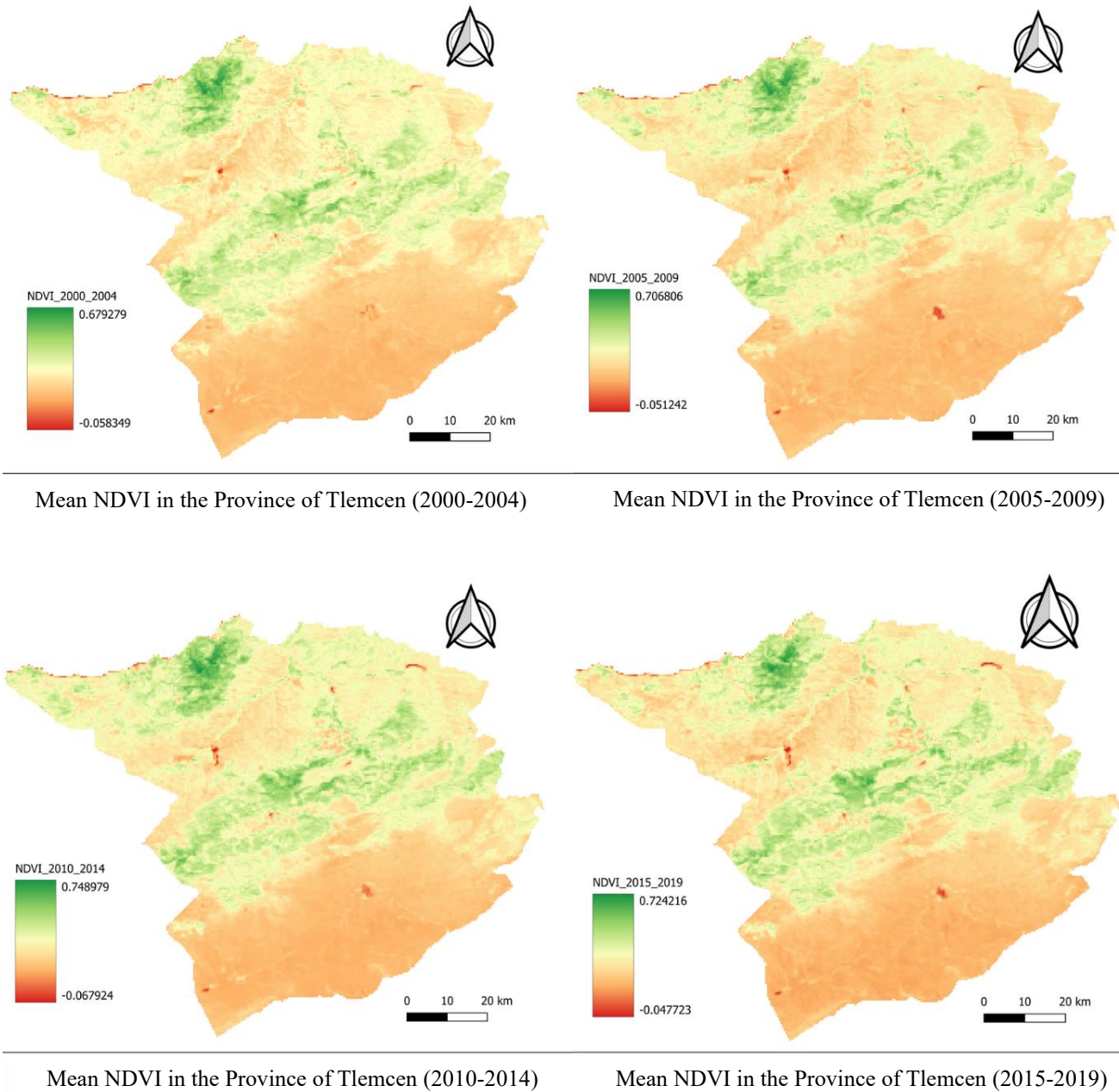


Figure 15: Normalized Difference Vegetation Index (NDVI) maps derived from MODIS MOD13Q1 (2000-2019) showing vegetation health evolution across Tlemcen Province, Algeria.

Notably, the interquartile range of NDVI widened during the study period, suggesting increased spatial heterogeneity in vegetation conditions. This growing dispersion indicates that while some areas maintained or improved vegetation health, others experienced degradation, resulting in a more fragmented landscape in terms of vegetation vigor.

5.2.2 EVI patterns

Enhanced Vegetation Index (EVI), which provides improved sensitivity in high biomass regions and better soil background correction, showed a pattern similar to NDVI but with a slightly more pronounced positive trend (slope = 0.0046/period, $r^2 = 0.548$, p-value = 0.260). Mean EVI increased from 0.168 in 2000-2004 to 0.186 in 2010-2014, followed by a slight decrease to 0.180 in 2015-2019 (Figure 16).

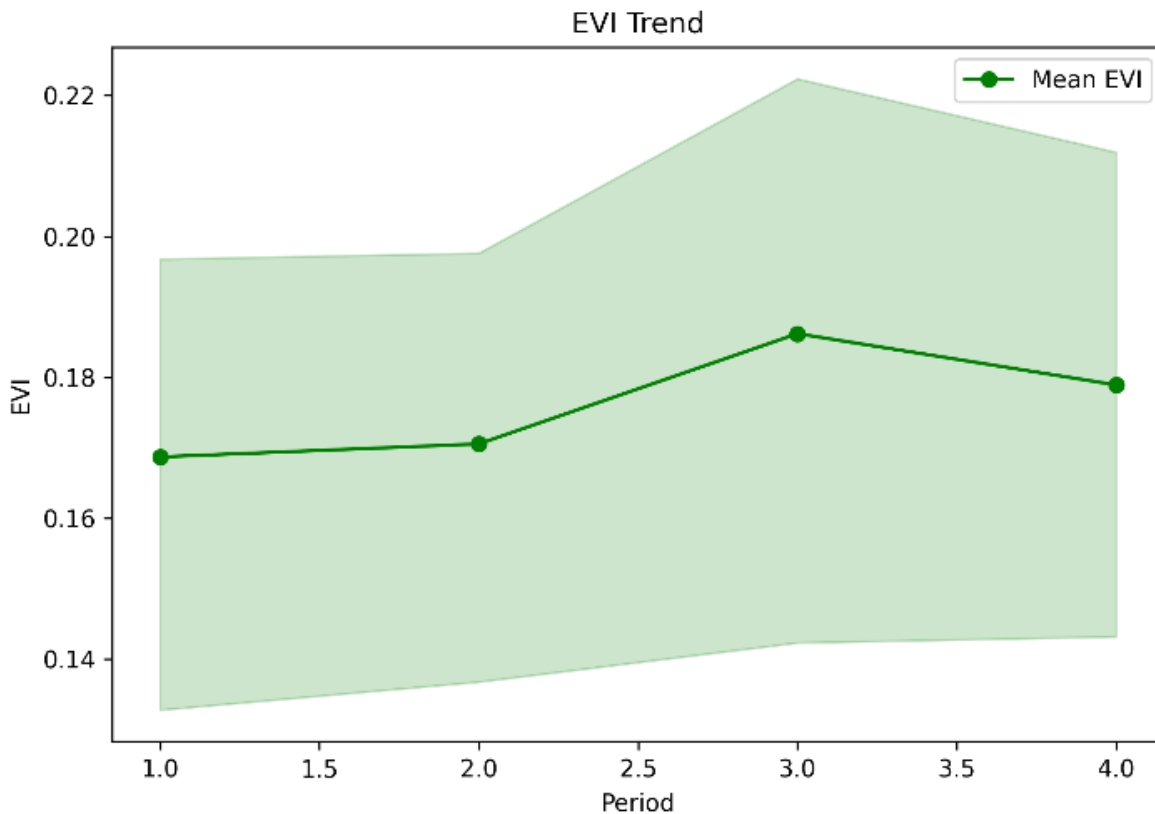


Figure 16: Enhanced Vegetation Index (EVI) evolution derived from MODIS MOD13Q1 (2000-2019) for Tlemcen Province, Algeria.

The spatial distribution of EVI (Figure 17) reveals a pattern consistent with NDVI, with higher values in the forested northern regions. However, EVI showed better discrimination in densely vegetated areas, highlighting differences in forest condition that were less apparent in the NDVI maps.

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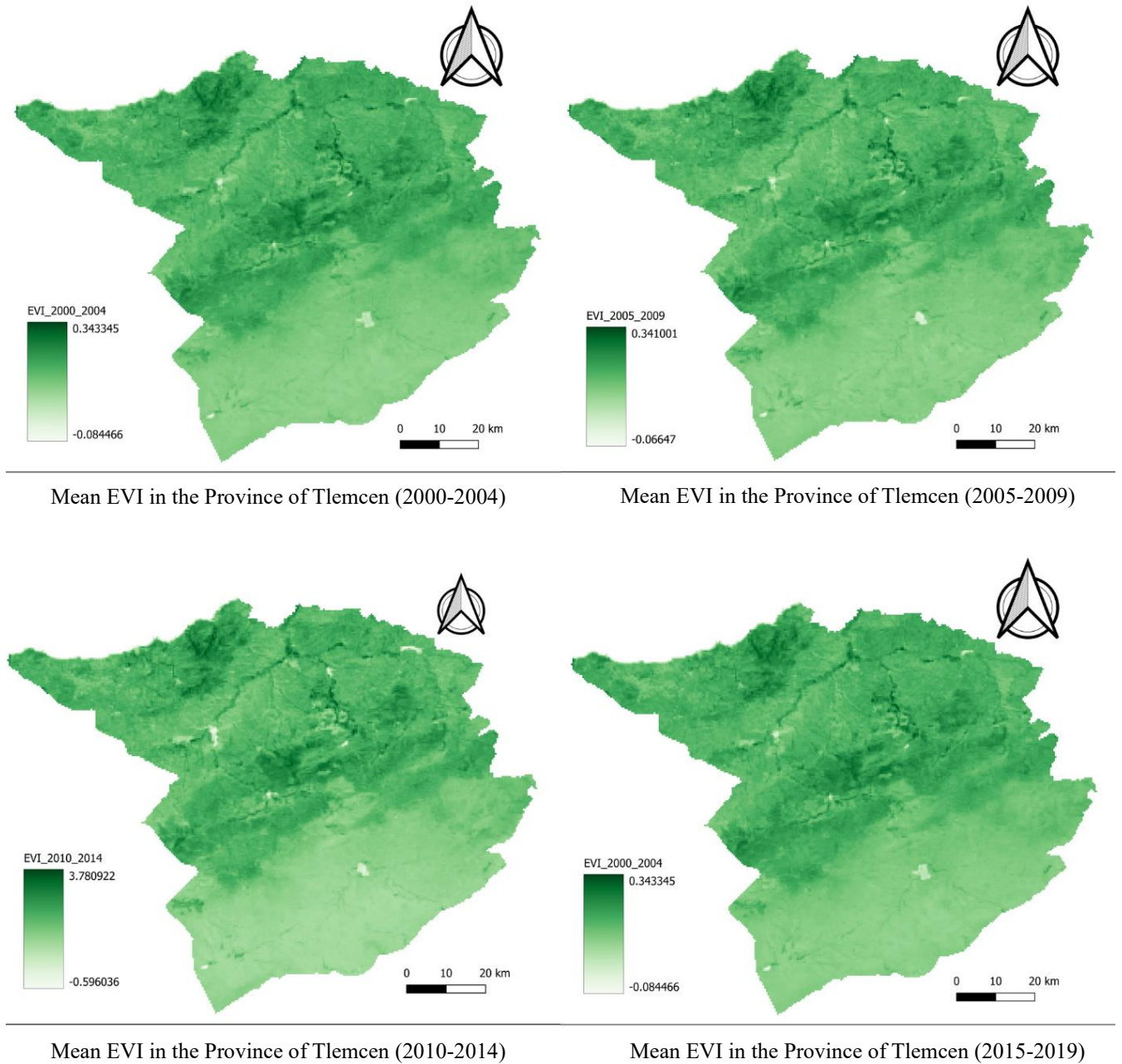


Figure 17: Enhanced Vegetation Index (EVI) maps derived from MODIS MOD13Q1 (2000-2019) for Tlemcen Province, Algeria.

Both vegetation indices exhibited parallel trajectories over time, with a correlation coefficient of $r = 1.00$ (Pearson) and $\rho = 1.00$ (Spearman). This perfect correlation confirms that despite their different sensitivities to canopy structure and background effects, both indices captured the same fundamental vegetation dynamics in the region.

5.2.3 Climate-vegetation relationships

Vegetation health showed significant correlations with climate variables. NDVI displayed a moderate positive correlation with precipitation (Pearson's $r = 0.60$, Spearman's $\rho = 0.80$) and a moderate negative correlation with temperature (Pearson's $r = -0.67$, Spearman's $\rho = -0.80$). Similarly, EVI was positively correlated with precipitation (Pearson's $r = 0.61$, Spearman's $\rho = 0.80$) and negatively correlated with temperature (Pearson's $r = -0.64$, Spearman's $\rho = -0.80$).

These correlations indicate that vegetation health in Tlemcen Province responds positively to increased moisture availability and negatively to thermal stress. The strongest climate-vegetation coupling occurred during the third period (2010-2014), when peak precipitation coincided with maximum NDVI and EVI values, suggesting that water availability was the primary limiting factor for vegetation health in this semi-arid region.

5.3 Wildfire Activity Patterns

5.3.1 Fire frequency trends

Fire frequency in Tlemcen Province decreased substantially over the study period (slope = -110.39 fires/period, $r^2 = 0.643$, p -value = 0.198). Mean annual fire counts declined from approximately 522 fires in 2000-2004 to 135 fires in 2010-2014, followed by a slight increase to 176 fires in 2015-2019 (Figure 18). While this declining trend was pronounced, it did not reach statistical significance due to the limited number of time periods.

The spatial distribution of fire occurrences was not uniform across the province. The Tlemcen and Trara mountains experienced the highest fire frequency, particularly during the first period (2000-2004). These mountainous areas are predominantly covered by mixed forests (MODIS class 5) and woody shrublands (MODIS classes 6-7), providing continuous, flammable fuel loads conducive to fire spread. In contrast, the plain regions, despite having drier conditions, recorded fewer fires. This reduced fire activity can be attributed not only to lower fuel loads but also to different land use patterns, as plains are dominated by croplands (MODIS class 12) and cropland/natural vegetation mosaics (MODIS class 14). These agricultural landscapes create a fragmented fuel pattern due to field boundaries, seasonal cultivation practices, and human management that limits fire spread. Additionally, the plains experience more intensive land management through agricultural activities, which may include controlled burning and vegetation clearing that reduce wildfire risk.

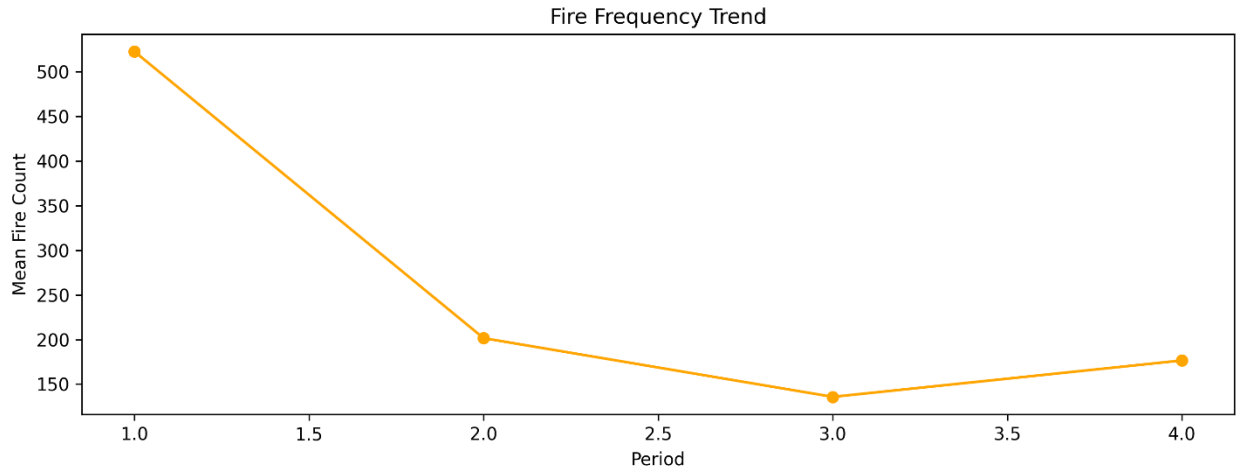


Figure 18: Fire frequency evolution derived from FireCCI burned area products (2000-2019) for Tlemcen Province, Algeria.

5.3.2 Burned area dynamics

Burned area showed variable patterns across the four time periods, with fluctuating medians and different distributions, rather than a simple decreasing trend (Figure 19).

The burned area in Tlemcen Province fluctuated across the four periods studied. The interquartile range was widest in Period 2 (150-220 hectares) with maximum values reaching nearly 500 hectares, while Period 1 showed a higher median (approximately 215 hectares) with extremes up to 450 hectares. Period 3 displayed the highest median burned area (around 225 hectares) with upper extremes reaching 420 hectares. Period 4 showed a slight decrease in burned area variability with a compressed range (200-225 hectares) and maximum values of about 385 hectares. Throughout all periods, the minimum burned area generally remained above 150 hectares, indicating a consistent baseline of fire impact in the region.

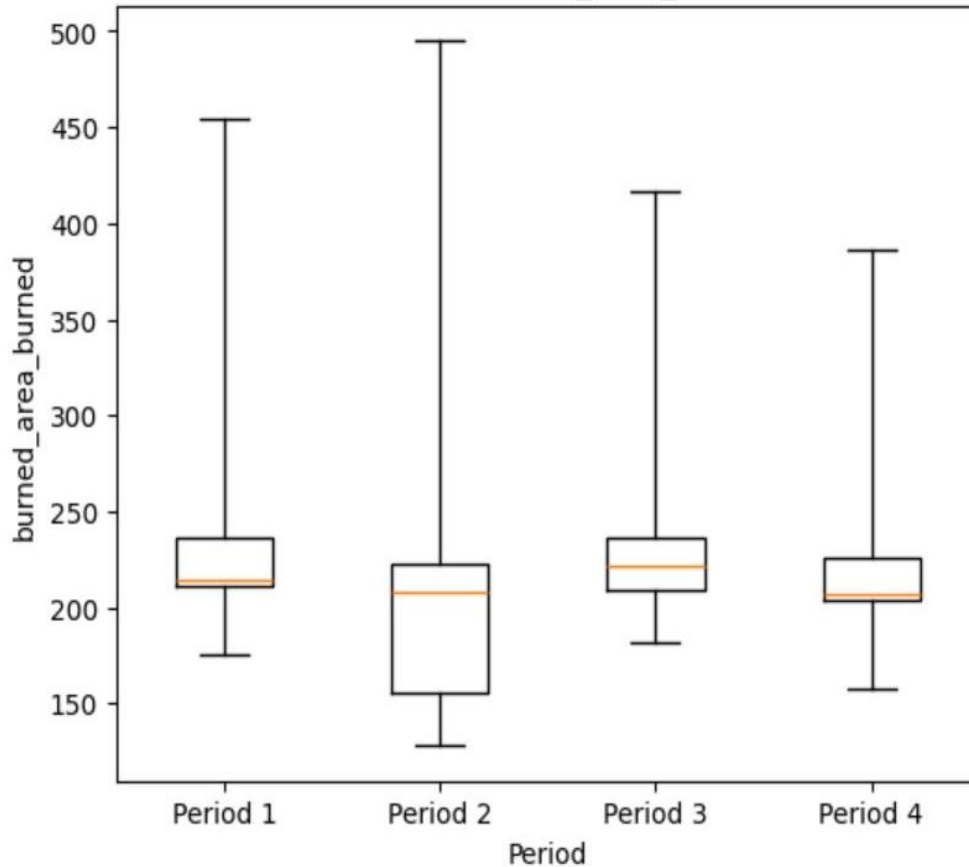


Figure 19: Box Plot of Burned Area Distribution Across Four Time Periods in Tlemcen Province, Algeria (2000-2019)

5.3.3 Climate-fire relationships

Fire activity showed strong correlations with climate variables. Both fire frequency and burned area were negatively correlated with precipitation (Pearson's $r = -0.61$, Spearman's $\rho = -0.80$) and positively correlated with temperature (Pearson's $r = 0.88$, Spearman's $\rho = 0.80$). These relationships align with ecological expectations, as higher temperatures increase fuel dryness and fire ignition probability, while precipitation reduces fire risk by increasing fuel moisture content.

The correlation matrices (Figure 20 and 21) visually illustrate these relationships, showing the strength and direction of associations between all studied variables. The matrices reveal strong negative correlations between temperature and precipitation (Pearson's $r = -0.90$, Spearman's $\rho = -1.00$), as well as the significant negative relationship between vegetation indices and fire metrics (Pearson's $r = -0.78$, Spearman's $\rho = -1.00$).

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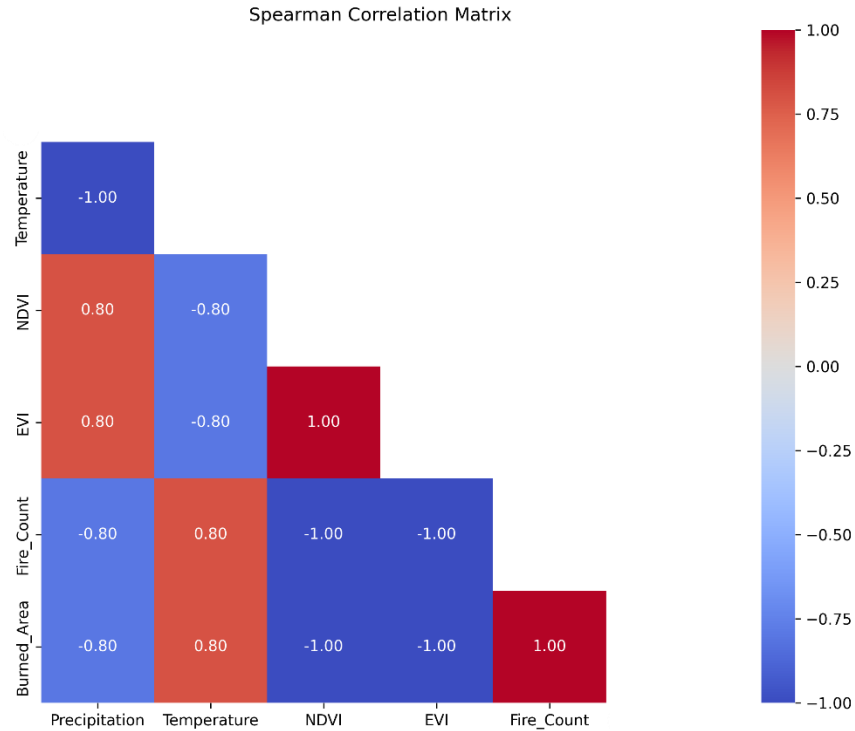


Figure 20: spearman correlation matrix showing relationships between climate variables, vegetation indices, and fire metrics for Tlemcen Province (2000-2019)

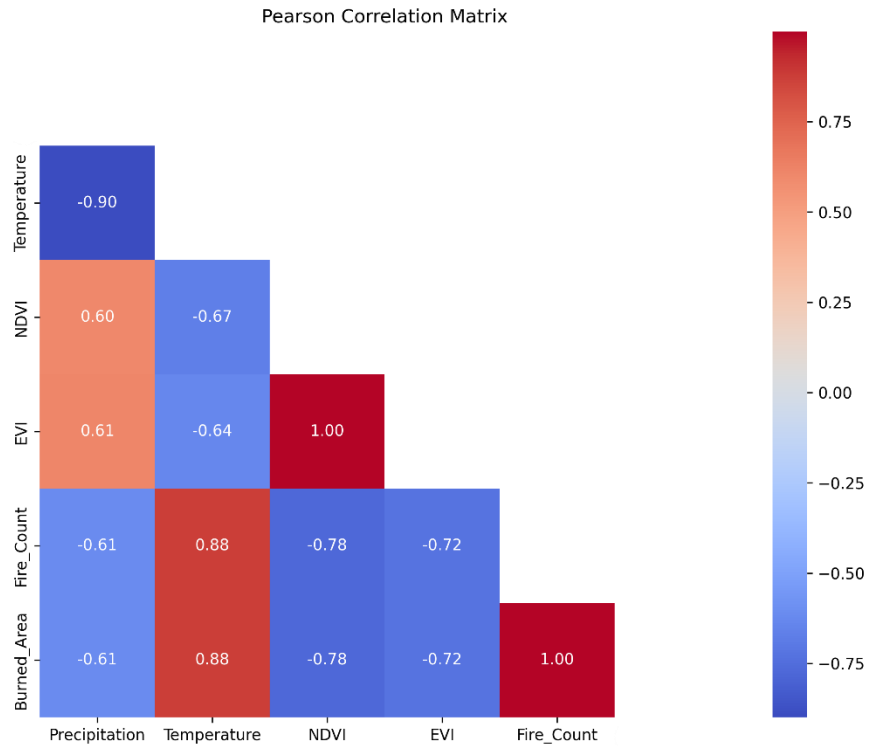


Figure 21: Pearson correlation matrix showing relationships between climate variables, vegetation indices, and fire metrics for Tlemcen Province (2000-2019)

The strongest climate-fire coupling occurred during the first period (2000-2004), which experienced relatively high temperatures, moderate precipitation, and maximum fire activity. Conversely, the third period (2010-2014) recorded minimum fire activity coinciding with peak precipitation and minimum temperature, further supporting the climate-fire relationship.

5.3.4 Vegetation-fire interactions

Both NDVI and EVI showed strong negative correlations with fire frequency (Pearson's $r = -0.78$, Spearman's $\rho = -1.00$) and burned area (Pearson's $r = -0.78$, Spearman's $\rho = -1.00$). This inverse relationship may seem counterintuitive since higher vegetation biomass typically provides more fuel for fires. However, in this Mediterranean semi-arid context, the negative correlation likely reflects that healthier vegetation (higher NDVI/EVI) indicates higher moisture content and reduced flammability.

The bubble plot visualization (Figure 22) illustrates this complex relationship, showing how areas with lower NDVI values experienced larger burned areas, particularly when combined with higher temperatures and increased fire frequency.

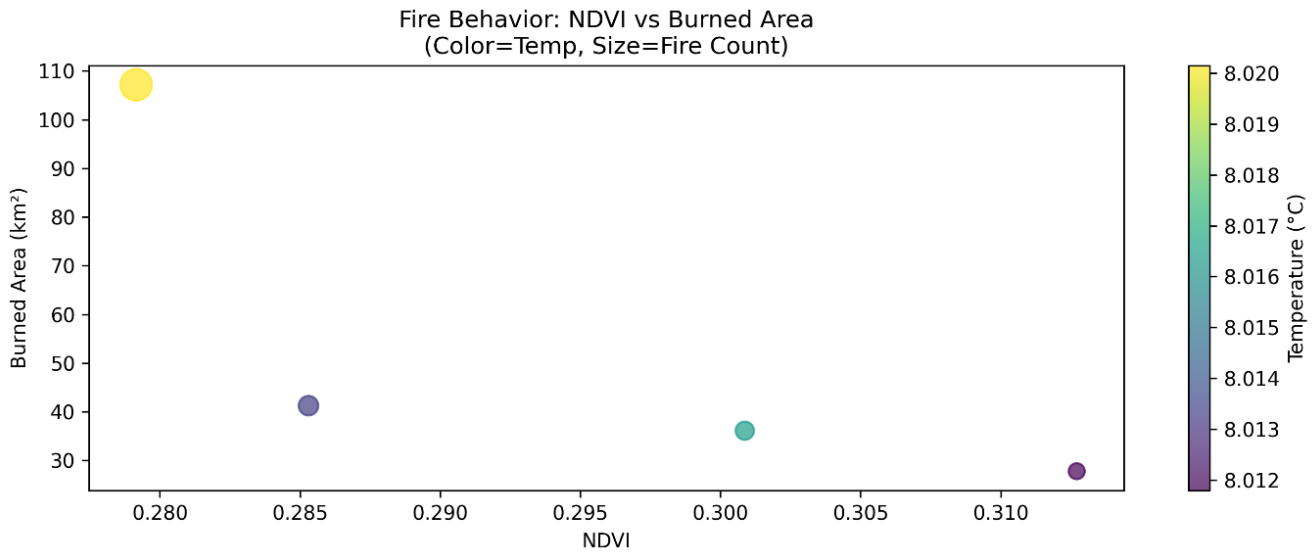


Figure 22: Relationship between NDVI, burned area, and temperature in Tlemcen Province (2000-2019). Bubble size represents fire frequency; color represents mean temperature

5.4 Land Cover Change and Its Implications

5.4.1 Land cover transitions

Comparison of land cover maps between 2001 and 2019 revealed significant transitions in the landscape composition of Tlemcen Province. The most notable changes included:

1. A decrease in forest cover from 12.8% to 10.5% of the total area (a net loss of approximately 23,000 hectares)
2. An expansion of shrublands from 31.5% to 36.2% (a net gain of approximately 47,000 hectares)
3. A slight increase in sparsely vegetated and bare areas from 18.3% to 19.7%
4. A decrease in agricultural lands from 36.2% to 32.3%

These transitions reflect both direct human impacts (e.g., forest clearing, agricultural abandonment) and indirect climate-induced vegetation changes (e.g., forest degradation to shrubland).

5.5 Discussion

5.5.1 Climate variability and vegetation response

The climate patterns observed in Tlemcen Province during 2000-2019 reflect broader Mediterranean climate dynamics, where increased variability rather than directional change has been identified as a dominant climate change signature (Lionello and Scarascia, 2018). The non-significant trends in both precipitation and temperature, coupled with widening interquartile ranges, suggest that environmental extremes rather than changes in mean conditions may be the primary drivers of ecological impacts in this region, consistent with findings across the western Mediterranean basin (Páscoa et al., 2017).

The moderate correlations between climate variables and vegetation indices (NDVI and EVI) indicate that while climate influences vegetation health, other factors also play important roles. Water availability appears to be the primary limiting factor, as evidenced by the stronger correlation between precipitation and vegetation indices compared to temperature-vegetation relationships. This finding aligns with studies in similar semi-arid regions that have identified precipitation as the dominant driver of vegetation dynamics (Vicente-Serrano et al., 2013; Gouveia et al., 2017).

The temporal patterns in vegetation response to precipitation events suggest that vegetation health reflects cumulative water availability rather than immediate rainfall conditions. This temporal dependency has been documented in other Mediterranean ecosystems (Gouveia et al., 2017) and has important implications for predicting ecosystem responses to climate fluctuations.

5.5.2 Fire regime dynamics and drivers

The variable pattern in burned area across the study period, with fluctuating medians and distribution ranges, contrasts with more consistent trends observed in some other Mediterranean regions. While parts of the European Mediterranean have experienced increased fire occurrence associated with warming temperatures (Turco et al., 2016), the pattern in Tlemcen Province suggests regional variation in fire regime responses. Several factors may explain this unexpected pattern:

- Fuel limitation hypothesis: The high fire activity in the early 2000s may have reduced fuel loads, creating a negative feedback loop that limited subsequent fire spread regardless of climate conditions, a phenomenon documented in other Mediterranean landscapes (Fernandes et al., 2016).
- Improved fire management: Enhanced fire prevention and suppression efforts implemented after the devastating fires of the mid 90s and early 2000s may have contributed to reduced fire activity despite conducive climate conditions, similar to trends observed in managed Mediterranean forests in Portugal and Spain (Moreira et al., 2020).
- Land use changes: The transition from forest to shrubland may have altered fuel connectivity and fire behavior in ways that modified large fire development, consistent with findings on landscape heterogeneity effects on fire spread (Loepfe et al., 2012).

The strong correlation between temperature and fire activity (Pearson's $r = 0.88$) aligns with established fire ecology principles, as higher temperatures reduce fuel moisture and increase ignition probability (Pausas and Fernández-Muñoz, 2012). However, the equally strong negative correlation between vegetation indices and fire activity suggests that in this region, fire occurrence is more closely linked to vegetation moisture stress than to biomass quantity.

5.5.3 Vegetation-climate-fire interactions

The triangular relationship between vegetation, climate, and fire reveals complex feedback mechanisms operating in Tlemcen Province. Our results showing decreased fire activity during periods of higher precipitation and healthier vegetation (higher NDVI/EVI), despite greater fuel availability, align with findings from Fernandes (2013) demonstrating the dominant role of fuel moisture in controlling Mediterranean fire regimes.

This pattern supports the concept that in Mediterranean semi-arid ecosystems, fire regimes are primarily "dryness-limited" rather than "fuel-limited." Unlike more mesic ecosystems where fuel accumulation drives fire cycles, in Tlemcen Province, critical fire weather conditions appear to be the dominant control on fire activity, consistent with the climate-fire relationship models proposed by Batllori et al. (2013) for Mediterranean ecosystems.

The statistical relationships uncovered in this study support a conceptual model where climate variability drives vegetation health, which in turn influences fire susceptibility, with important feedbacks from fire disturbance to subsequent vegetation recovery. This integrated understanding

provides a framework for predicting ecosystem responses consistent with observed patterns in other Mediterranean regions (Vilar et al., 2016).

5.5.4 Implications of land cover change

The observed land cover transitions, particularly the conversion from forest to shrubland, represent a significant ecosystem alteration with multiple environmental implications. This shift toward a more xeric landscape structure may reflect climate adaptation processes, as drought-resistant shrub species replace more moisture-dependent forest vegetation, a pattern observed across multiple Mediterranean landscapes (Acácio et al., 2017).

The expansion of shrublands has contradictory implications for fire regimes. Research by Moreira et al. (2011) demonstrates that in the short term, this expansion may increase fire risk by creating a more flammable landscape mosaic with fine fuels that dry quickly. However, Fernandes (2013) notes that in the longer term, reduced fuel loads and continuity in shrubland ecosystems may limit the spread of catastrophic fires.

From a carbon storage perspective, the conversion from forest to shrubland represents a net loss of ecosystem carbon stocks. Studies in comparable Mediterranean ecosystems (Ruiz-Peinado et al., 2013) indicate that such transitions can significantly impact regional carbon budgets and potentially contribute to climate feedbacks.

5.5.5 Limitations of the study

Several limitations should be considered when interpreting these results:

- Fire data accuracy: Reliance on satellite-detected burned areas may underestimate small fires, particularly in the earlier periods when sensor resolutions were lower, a limitation acknowledged in similar remote sensing studies (Ruffault and Mouillot, 2015).
- Attribution challenges: While statistical correlations between variables are strong, establishing causal relationships remains challenging given the complex interactions and potential confounding factors.
- Limited number of time periods: With only four time periods, statistical power for trend detection is limited, reducing the ability to identify significant trends despite potentially meaningful ecological changes.

5.5.6 Recommendations for future research

Based on the findings and limitations of this study, several avenues for future research emerge:

- Enhanced temporal analysis: Future studies should consider annual time-series analysis to better capture interannual variability and extreme events that may be masked by period aggregation.
- Mechanistic modeling: Development of process-based models that incorporate vegetation growth, moisture dynamics, and fire behavior would enhance understanding of causal mechanisms beyond statistical correlations.

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- Field validation: Ground-based measurements of vegetation moisture content, fuel loads, and fire effects would provide essential validation of remote sensing-based inferences.
- Climate projection integration: Integrating these empirical findings with regional climate projections would improve predictions of future fire regimes and vegetation dynamics under climate change scenarios.
- Socio-ecological approach: Incorporating human dimensions, including land management practices, fire policies, and rural socioeconomic changes, would provide a more comprehensive understanding of ecosystem changes.
- Comparative studies: Extending this analytical framework to other Mediterranean regions would help identify common patterns versus site-specific dynamics in climate-vegetation-fire relationships.

5.5.7 Management implications

The findings from this study have several implications for land and fire management in Tlemcen Province:

- Adaptive fire management: Fire prevention and suppression strategies should adapt to the changing landscape structure, with particular attention to forest-shrubland interfaces where fire risk may be elevated.
- Vegetation monitoring: The widening interquartile ranges in vegetation indices suggest increasing spatial heterogeneity, highlighting the need for spatially targeted management approaches rather than province-wide uniform strategies.
- Ecosystem resilience: Conservation efforts should prioritize maintaining intact forest patches, which showed greater stability in vegetation indices throughout climate fluctuations, suggesting enhanced ecological resilience.
- Climate adaptation planning: The strong climate-vegetation-fire linkages identified in this study underscore the importance of incorporating climate change projections into long-term land management and fire mitigation planning.
- Carbon management: Given the carbon implications of forest-to-shrubland transitions documented in Mediterranean ecosystems (Ruiz-Peinado et al., 2013), reforestation and forest conservation initiatives could deliver climate mitigation benefits while enhancing ecosystem services.

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This research set out to investigate the complex interactions between climate patterns, vegetation dynamics, and wildfire activity in Tlemcen Province, Algeria over a twenty-year period (2000-2019). The study employed an integrated methodological approach combining remote sensing, Geographic Information Systems (GIS), and statistical analysis to detect and quantify environmental changes across this Mediterranean landscape. By analyzing time series data aggregated into four 5-year periods, the research sought to identify both directional trends and shifting patterns of variability in key environmental parameters.

The findings reveal a nuanced ecological system where climate variability, rather than directional climate change, emerged as the dominant driver of vegetation health and fire regimes. While precipitation showed a non-significant increasing trend followed by a recent decline, and temperatures exhibited minor fluctuations, it was the widening interquartile ranges in both climate variables that signaled increased environmental extremes. This pattern of growing climatic variability aligns with broader predictions for Mediterranean regions under global change scenarios.

Vegetation health, as measured by NDVI and EVI, demonstrated remarkable resilience through the study period, maintaining relatively stable mean values despite climate fluctuations. However, the spatial distribution of vegetation vigor became increasingly heterogeneous, with widening percentile bands indicating greater disparity between healthy and stressed vegetation patches. This spatial divergence in vegetation condition suggests differential resilience and vulnerability across the landscape, potentially linked to underlying factors such as topography, soil conditions, and land use history.

Perhaps the most unexpected finding emerged in the wildfire activity patterns, which showed variable burned area distributions across the study periods rather than a consistent trend, despite conditions that might theoretically favor more predictable fire occurrence patterns. This counterintuitive trend highlights the complex interplay between climate, vegetation, and disturbance regimes in Mediterranean ecosystems. The inverse relationship between vegetation indices and fire metrics suggests that in Tlemcen Province, fire regimes are primarily controlled by vegetation moisture status rather than biomass accumulation, making them more responsive to drought conditions than fuel availability.

Land cover transitions, particularly the conversion from forest to shrubland, represent one of the most significant environmental changes documented in this study. This landscape transformation both influences and is influenced by climate-vegetation-fire dynamics, creating complex feedback mechanisms that shape ecosystem trajectories. The forest-to-shrubland transition represents not only a change in vegetation structure but also potential alterations to ecosystem services, carbon storage capacity, and future disturbance susceptibility.

CHAPTER 6: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The methodological approach developed in this research offers a robust framework for integrated environmental monitoring that could be applied to other Mediterranean regions facing similar challenges. By combining multiple remote sensing indices, climate metrics, and fire statistics, the study provides a more comprehensive picture of ecosystem dynamics than single-factor analyses. The incorporation of percentile bands rather than simple means allows for the detection of changing variability patterns that may be more ecologically significant than shifts in average conditions.

From a theoretical perspective, this research contributes to the evolving understanding of Mediterranean ecosystem responses to environmental change. The findings challenge simplistic models of climate-fire relationships by demonstrating how context-specific factors can modulate expected responses. In particular, the documentation of decreasing fire activity despite climate conditions that might theoretically increase fire risk highlights the importance of considering multiple interacting factors rather than isolated drivers when predicting ecosystem trajectories.

For land managers and policymakers in Tlemcen Province and similar Mediterranean regions, several practical implications emerge from this research. First, the increasing spatial heterogeneity in vegetation condition calls for more targeted and spatially explicit management approaches rather than uniform strategies across large landscapes. These could include strategic mosaic fuel reduction treatments focused on high-risk forest-shrubland interfaces, microclimate-based water management systems with small check dams in stress-prone areas, differential fire management zones that vary suppression levels by vegetation type, and site-specific ecological restoration using species selected according to local conditions. Second, the documented resilience of intact forest patches suggests that conservation efforts should prioritize maintaining these ecological anchors that can buffer against climate extremes. Third, the shifting relationship between climate, vegetation, and fire underscores the need for adaptive management strategies that can respond to changing disturbance regimes.

Based on these findings, several recommendations for environmental management in Tlemcen Province can be offered. Conservation efforts should focus on preserving and enhancing landscape connectivity between intact forest patches, which appear to serve as islands of resilience in an increasingly fragmented landscape. Revegetation initiatives should carefully consider species selection in light of observed climate trends, potentially favoring drought-adapted species that can withstand the increasing variability documented in this study. Fire management strategies should evolve from a primary focus on suppression to a more integrated approach that accounts for changing fuel dynamics and recognizes the potential ecological benefits of appropriate fire regimes.

For the academic and research community, this study highlights several avenues for future investigation. Annual time-series analysis would provide greater temporal resolution than the 5-year periods used here, potentially revealing important interannual dynamics and extreme event impacts that may be masked by temporal aggregation. Field-based validation of remote sensing

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metrics, particularly measurements of vegetation moisture content and fuel characteristics, would strengthen the inferences drawn from satellite data. Integration of socioeconomic factors, including land use practices, demographic changes, and policy interventions, would provide a more comprehensive understanding of the human dimensions that influence environmental change in this region.

The analytical framework developed in this research has potential applications beyond Tlemcen Province. Similar approaches could be applied to other Mediterranean regions to assess whether the patterns observed here represent site-specific dynamics or reflect broader regional trends. Comparative studies across multiple Mediterranean landscapes would help identify common response patterns versus context-dependent variations, enhancing our ability to develop transferable management principles.

The findings from this study can inform climate adaptation planning in several ways. The documented resilience of certain landscape elements provides insights into natural adaptation mechanisms that could be leveraged in climate-smart land management. The unexpected trends in fire activity highlight the dangers of overly simplistic climate-fire projections and underscore the need for more nuanced, contextually grounded predictive models. The integration of remote sensing, climate data, and disturbance metrics demonstrates a practical approach to environmental monitoring that could support early warning systems for ecosystem change.

Several questions remain unanswered and warrant further research. The mechanisms driving the observed decrease in fire activity despite theoretically favorable climate conditions require deeper investigation, potentially incorporating factors not addressed in this study such as ignition sources and suppression effectiveness. The long-term sustainability of the observed landscape transitions, particularly the forest-to-shrubland conversion, remains uncertain and would benefit from longer monitoring timeframes. The potential consequences of increasing spatial heterogeneity in vegetation condition for ecosystem processes, including water cycling, carbon sequestration, and biodiversity maintenance, represent important knowledge gaps that future studies should address.

In conclusion, this research provides a comprehensive assessment of environmental change in Tlemcen Province over two decades, revealing complex interactions between climate, vegetation, and fire regimes. The findings highlight the importance of considering variability patterns alongside directional trends, spatial heterogeneity alongside mean conditions, and multiple interacting factors rather than isolated drivers. By enhancing our understanding of Mediterranean ecosystem dynamics, this study contributes to the scientific foundation needed for adaptive environmental management in the face of ongoing global change. The methodological approaches developed here offer practical tools for monitoring and assessing complex environmental systems, while the empirical findings provide insights relevant to both ecological theory and land management practice.

REFERENCES

7. REFERENCES

- Aboura, R. (2006). Comparaison phytoécologique des Atriplexaies situées au nord et au sud de Tlemcen. Mémoire de Magistère, Université de Tlemcen, 160p.
- Acácio, V., Dias, F. S., Catry, F. X., Rocha, M., & Moreira, F. (2017). Landscape dynamics in Mediterranean oak forests under global change: understanding the role of anthropogenic and environmental drivers across forest types. *Global Change Biology*, 23(3), 1199-1217.
- Alcaraz-Segura, D., Cabello, J., Paruelo, J. M., & Delibes, M. (2009). Use of descriptors of ecosystem functioning for monitoring a national park network: a remote sensing approach. *Environmental Management*, 43(1), 38-48.
- Batllori, E., Parisien, M. A., Krawchuk, M. A., & Moritz, M. A. (2013). Climate change-induced shifts in fire for Mediterranean ecosystems. *Global Ecology and Biogeography*, 22(10), 1118-1129.
- Belgherbi, B., & Benabdeli, K. (2021). First structural analysis of the burnt areas by forest fires in the Tlemcen National Park, Algeria. *Euro-Mediterranean Journal for Environmental Integration*, 6(2), 1-12.
- Benabadji, N., & Bouazza, M. (1998). Composition floristique et pression anthropozoïque au Sud-Ouest de Tlemcen. *Revue Sciences et Technologie*, 10, 93-97.
- Benabadji, N., & Bouazza, M. (2000). Quelques modifications climatiques intervenues dans le Sud-Ouest de l'Oranie (Algérie occidentale). *Revue d'Écologie et Environnement*, 16, 7-18.
- Benabadji, N., & Bouazza, M. (2001). L'impact de l'homme sur la forêt dans la région de Tlemcen. *Forêt Méditerranéenne*, 22(3), 269-274.
- Benabdeli, K. (1983). Mise au point d'une méthodologie d'appréciation de la pression anthropozoïque sur la végétation dans la région de Tlemcen. Thèse de Doctorat de 3ème cycle, Université d'Aix-Marseille III, 185p.
- Benabdeli, K. (1996). Aspects physionomico-structuraux de la végétation ligneuse forestière face à la pression anthropozoogène dans les monts de Tlemcen et les monts de Dhaya (Algérie occidentale). Thèse Doct. d'Etat, Université Sidi Bel Abbès, 356p.
- Benabdeli, K. (1996). Impact socio-économique et écologique de la privatisation des terres sur la gestion des espaces et la conduite des troupeaux: cas de la commune de Télagh (Algérie). *Options Méditerranéennes*, 32, 185-194.
- Bentchakal, M., Medjerab, A., Chibane, B. et al. (2022). Meteorological drought and remote sensing data: an approach to assess fire risks in the Algerian forest. *Model. Earth Syst. Environ.* 8, 3847–3858. <https://doi.org/10.1007/s40808-021-01323-0>

REFERENCES

- Bento-Gonçalves, A., & Vieira, A. (2020). Wildfires in the wildland-urban interface: Key concepts and evaluation methodologies. *Science of the Total Environment*, 707, 135592.
- Bestaoui, K. (2001). Contribution à une étude syntaxonomique et écologique des matorrals de la région de Tlemcen. Thèse de Magister, Université de Tlemcen, 184p.
- Bouazza, M., & Benabadji, N. (1998). Composition floristique et pression anthropozoïque au Sud-Ouest de Tlemcen. *Revue Sciences et Technologie*, 10, 93-97.
- Bouazza, M., Mahboubi, A., Loisel, R., & Benabadji, N. (2001). Bilan de la flore de la région de Tlemcen (Oranie-Algérie). *Forêt Méditerranéenne*, 22(2), 130-136.
- Bouhraoua, R.T., & Villemant, C. (2005). Mécanismes généraux de l'altération sanitaire des peuplements de chêne-liège de l'Algérie nord-occidentale. *IOBC/wprs Bulletin*, 28(8), 1-8.
- Chuvieco, E., Aguado, I., Jurdao, S., Pettinari, M. L., Yebra, M., Salas, J., Hantson, S., de la Riva, J., Ibarra, P., Rodrigues, M., Echeverría, M., Azqueta, D., Román, M. V., Bastarrika, A., Martínez, S., Recondo, C., Zapico, E., & Martínez-Vega, F. J. (2014). Integrating geospatial information into fire risk assessment. *International Journal of Wildland Fire*, 23(5), 606-619.
- Chuvieco, E., Yebra, M., Jurdao, S., Aguado, I., Salas, F. J., García, M., Nieto, H., de Santis, A., Cocero, D., Riaño, D., Martínez, S., Zapico, E., Recondo, C., Martínez-Vega, J., Martín, M. P., Riva, J., Pérez, F., & Rodríguez-Silva, F. (2012). Integrating geospatial information into fire risk assessment. *International Journal of Wildland Fire*, 21(2), 69-86.
- Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J. P., Iglesias, A., Lange, M. A., Lionello, P., Llasat, M. C., Paz, S., Peñuelas, J., Snoussi, M., Toreti, A., Tsimplis, M. N., & Xoplaki, E. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, 8(11), 972-980.
- Curt, T., Aini, A., & Dupire, S. (2020). Fire Activity in Mediterranean Forests (The Algerian Case). *Fire*, 3(4), 58. <https://doi.org/10.3390/fire3040058>
- Doblas-Miranda, E., Alonso, R., Arnan, X., Bermejo, V., Brotons, L., De las Heras, J., Estiarte, M., Hódar, J. A., Llorens, P., Lloret, F., López-Serrano, F. R., Martínez-Vilalta, J., Moya, D., Peñuelas, J., Pino, J., Rodrigo, A., Roura-Pascual, N., Valladares, F., Vilà, M., ... & Retana, J. (2017). A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: Beyond drought effects. *Global and Planetary Change*, 148, 42-54.
- Elbeltagi, A., El-Magd, M. S., El-Ghany, A. M., & El Nahry, A. H. (2020). A framework for drought assessment using remote sensing in Egypt. *Environmental Science and Pollution Research*, 27(22), 28402-28414.
- Fernandes, P. M. (2013). Fire-smart management of forest landscapes in the Mediterranean basin under global change. *Landscape and Urban Planning*, 110, 175-182.

REFERENCES

- Fernandes, P. M., Barros, A. M., Pinto, A., & Santos, J. A. (2016). Characteristics and controls of extremely large wildfires in the western Mediterranean Basin. *Journal of Geophysical Research: Biogeosciences*, 121(8), 2141-2157.
- Fox, D. M., Carrega, P., Ren, Y., Caillouet, P., Bouillon, C., & Robert, S. (2018). How wildfire risk is related to urban planning and Fire Weather Index in SE France (1990–2013). *Science of the Total Environment*, 621, 120-129.
- Ganteaume, A., & Barbero, R. (2019). Contrasting large fire activity in the French Mediterranean. *Natural Hazards and Earth System Sciences*, 19(5), 1055-1066.
- Gaouar, A. (1980). Hypothèses et réflexions sur la dégradation des écosystèmes forestiers dans la région de Tlemcen (Algérie). *Forêt Méditerranéenne*, 2(2), 131-146.
- Giorgi, F., Bi, X., & Pal, J. (2004). Mean, interannual variability and trends in a regional climate change experiment over Europe. II: climate change scenarios (2071–2100). *Climate Dynamics*, 23(7), 839-858.
- Giorgi, F., & Lionello, P. (2008). Climate change projections for the Mediterranean region. *Global and Planetary Change*, 63(2-3), 90-104.
- Gouveia, C. M., Bistinas, I., Liberato, M. L. R., Bastos, A., Koutsias, N., & Trigo, R. (2016). The modulating effect of drought on the relationship between vegetation and wildfire in southern European ecosystems. *Agricultural and Forest Meteorology*, 237-238, 171-184.
- Gouveia, C. M., Páscoa, P., Russo, A., & Trigo, R. M. (2016). Land degradation assessment over Iberia during 1982–2012. *Cuadernos de Investigación Geográfica*, 42(1), 89-112.
- Gouveia, C. M., Trigo, R. M., Beguería, S., & Vicente-Serrano, S. M. (2017). Drought impacts on vegetation activity in the Mediterranean region: An assessment using remote sensing data and multi-scale drought indicators. *Global and Planetary Change*, 151, 15-27.
- Haddouche, I., Benhanifia, K., & Gacemi, M. (2011). Analyse spatiale de feu de forêt en Algérie : cas de la Wilaya de Tlemcen. *Revue d'Écologie et Environnement*, 7, 54-62.
- Hasnaoui, O. (2008). Contribution à l'étude de la chamaeropaie de la région de Tlemcen: aspects écologiques et cartographie. Thèse de Doctorat, Université de Tlemcen, 208p.
- Hasnaoui, O., Bouazza, M., Benali, O., & Thinon, M. (2011). Étude de la diversité floristique des matorrals dérivant des subéraies de la région de Tlemcen (Algérie occidentale). *Continental Journal of Biological Sciences*, 4(1), 8-18.
- Keeley, J. E., Bond, W. J., Bradstock, R. A., Pausas, J. G., & Rundel, P. W. (2011). *Fire in Mediterranean ecosystems: Ecology, evolution and management*. Cambridge University Press.
- Koutsias, N., Allgöwer, B., Kalabokidis, K., Mallinis, G., Balatsos, P., & Goldammer, J. G. (2016). Fire occurrence zoning from local to global scale in the European Mediterranean basin:

REFERENCES

Implications for multi-scale fire management and policy. *iForest - Biogeosciences and Forestry*, 9(2), 195-204.

- Kumareswaran, K., Jayasinghe, G.Y. (2023). Climate Resilience and Sustainable Cities. In: *Green Infrastructure and Urban Climate Resilience*. Springer, Cham. https://doi.org/10.1007/978-3-031-37081-6_2
- Leone, V., Lovreglio, R., Martín, M. P., Martínez, J., & Vilar, L. (2009). Human factors of fire occurrence in the Mediterranean. In E. Chuvieco (Ed.), *Earth observation of wildland fires in Mediterranean ecosystems* (pp. 149-170). Springer.
- Letreuch-Belarouci, A., Medjahdi, B., Letreuch-Belarouci, N., & Benabdeli, K. (2009). Diversité floristique des subéraies du parc national de Tlemcen (Algérie). *Acta Botanica Malacitana*, 34, 77-89.
- Letreuch-Belarouci, N., Letreuch-Belarouci, A., Benabdeli, K., & Medjahdi, B. (2010). Impact des incendies sur la structure des peuplements de chêne-liège et sur le liège: le cas de la subéraie de Tlemcen, Algérie. *Forêt Méditerranéenne*, 31(1), 17-24.
- Lionello, P., & Scarascia, L. (2018). The relation between climate change in the Mediterranean region and global warming. *Regional Environmental Change*, 18(5), 1481-1493.
- Loepfe, L., Martinez-Vilalta, J., & Piñol, J. (2012). Management alternatives to offset climate change effects on Mediterranean fire regimes in NE Spain. *Climatic Change*, 115(3), 693-707.
- Médail, F., & Quézel, P. (2003). Conséquences écologiques possibles des changements climatiques sur la flore et la végétation du bassin méditerranéen. *Bocconea*, 16(1), 397-422.
- Meddi, M., Talia, A., & Martin, C. (2010). Evolution récente des conditions climatiques et des écoulements sur le bassin versant de la Macta (Nord-Ouest de l'Algérie). *Géographie Physique et Environnement*, 3, 61-84.
- Meddour-Sahar, O. (2015). Wildfires in Algeria: Problems and challenges. *International Symposium on Fire Economics, Planning, and Policy: Climate Change and Wildfires*, November 2015, Córdoba, Spain. USDA Forest Service, PSW-GTR-245, 15-30.
- Meddour-Sahar, O., & Derridj, A. (2012). Bilan des feux de forêts en Algérie: Analyse spatiotemporelle et cartographie du risque (1985-2010). *Sécheresse*, 23(2), 133-141.
- Meddour-Sahar, O., Meddour, R., Leone, V., Lovreglio, R., & Derridj, A. (2013). Analysis of forest fires causes and their motivations in northern Algeria: the Delphi method. *iForest-Biogeosciences and Forestry*, 6(4), 247-254.
- Medjahdi, B., Letreuch-Belarouci, A., Maazouz, S., & Taïbi, K. (2009). Diversité floristique des subéraies des monts de Tlemcen (Nord Ouest Algérien). *Geo-Eco-Trop*, 33, 1-10.

REFERENCES

- Moreira, F., Ascoli, D., Safford, H., Adams, M. A., Moreno, J. M., Pereira, J. M., Catry, F. X., Armesto, J., Bond, W., González, M. E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J. G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V. R., ... & Fernandes, P. M. (2020). Wildfire management in Mediterranean-type regions: paradigm change needed. *Environmental Research Letters*, 15(1), 011001.
- Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., & Bilgili, E. (2011). Landscape–wildfire interactions in southern Europe: implications for landscape management. *Journal of Environmental Management*, 92(10), 2389-2402.
- Oliveira, S., Zêzere, J. L., Queirós, M., & Pereira, J. M. (2017). Assessing the social context of wildfire-affected areas. The case of mainland Portugal. *Applied Geography*, 88, 104-117.
- Páscoa, P., Gouveia, C. M., Russo, A., & Trigo, R. M. (2017). The role of drought on wheat yield interannual variability in the Iberian Peninsula from 1929 to 2012. *International Journal of Biometeorology*, 61(3), 439-451.
- Pausas, J. G., & Fernández-Muñoz, S. (2012). Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change*, 110(1), 215-226.
- Pausas, J. G., Llovet, J., Rodrigo, A., & Vallejo, R. (2008). Are wildfires a disaster in the Mediterranean basin?—A review. *International Journal of Wildland Fire*, 17(6), 713-723.
- Pausas, J. G., & Vallejo, V. R. (1999). The role of fire in European Mediterranean ecosystems. In E. Chuvieco (Ed.), *Remote sensing of large wildfires in the European Mediterranean basin* (pp. 3-16). Springer.
- Quézel, P., & Santa, S. (1962-1963). *Nouvelle flore de l'Algérie et des régions désertiques méridionales*. CNRS, Paris, 1170p.
- Rodrigues, M., Gelabert, P. J., Ameztegui, A., Coll, L., & Vega-García, C. (2022). Has Covid-19 halted winter-spring wildfires in the Mediterranean? Insights for wildfire science under a pandemic context. *Science of the Total Environment*, 815, 152943.
- Ruffault, J., Curt, T., Martin-StPaul, N. K., Moron, V., & Trigo, R. M. (2018). Extreme wildfire events are linked to global-change-type droughts in the northern Mediterranean. *Natural Hazards and Earth System Sciences*, 18(3), 847-856.
- Ruffault, J., Curt, T., Moron, V. et al. (2020). Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. *Sci Rep* 10, 13790. <https://doi.org/10.1038/s41598-020-70069-z>
- Ruffault, J., & Mouillot, F. (2015). How a new fire-suppression policy can abruptly reshape the fire-weather relationship. *Ecosphere*, 6(10), 1-19.

REFERENCES

- Ruiz-Peinado, R., Bravo-Oviedo, A., López-Senespleda, E., Montero, G., & Río, M. (2013). Do thinnings influence biomass and soil carbon stocks in Mediterranean maritime pinewoods? *European Journal of Forest Research*, 132(2), 253-262.
- Salis, M., Arca, B., Alcasena-Urdiroz, F., Bacciu, V., Massaiu, A., Bosseur, F., Caballero, D., Sirca, C., Cocco, S., & Spano, D. (2021). Recent developments in forest fire risk mapping in Mediterranean areas. *Forests*, 12(3), 262.
- San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Libertà, G., Artés-Vivancos, T., Oom, D., Branco, A., de Rigo, D., Ferrari, D., Pfeiffer, H., Grecchi, R., & Nuijten, D. (2022). Forest fires in Europe, Middle East and North Africa 2021. Publications Office of the European Union.
- Santos, S. M. B. dos, Bento-Gonçalves, A., Vieira, A., & Teixeira, G. (2023). Assessment of vegetation regrowth and spatial patterns and severity factors of wildfires in wildland-urban interface: The case of the large wildfire in Baião (2019). *Cadernos de Geografia*, 47, 21-34. https://doi.org/10.14195/0871-1623_47_2
- Santos, S. M. B. dos, Duverger, S. G., Bento-Gonçalves, A., Franca-Rocha, W., Vieira, A., & Teixeira, G. (2023). Remote sensing applications for mapping large wildfires based on machine learning and time series in northwestern Portugal. *Fire*, 6(2), 43. <https://doi.org/10.3390/fire6020043>
- Sarris, D., Christodoulakis, D., & Körner, C. (2011). Impact of recent climatic change on growth of low-elevation eastern Mediterranean forest trees. *Climatic Change*, 106(2), 203-223.
- Slimani, S., Touchan, R., Derridj, A., Kherchouche, D., & Gutiérrez, E. (2014). Fire history of Atlas cedar (*Cedrus atlantica* Manetti) in Mount Chélia, northern Algeria. *Journal of Arid Environments*, 104, 116-124.
- Tabari, H., & Willems, P. (2018). Seasonally varying footprint of climate change on precipitation in the Middle East. *Scientific Reports*, 8(1), 4435.
- Tedim, F., Leone, V., Amraoui, M., Bouillon, C., Coughlan, M. R., Delogu, G. M., Fernandes, P. M., Ferreira, C., McCaffrey, S., McGee, T. K., Parente, J., Paton, D., Pereira, M. G., Ribeiro, L. M., Viegas, D. X., & Xanthopoulos, G. (2018). Defining extreme wildfire events: Difficulties, challenges, and impacts. *Fire*, 1(1), 9.
- Tessler, N., Wittenberg, L., & Greenbaum, N. (2016). Vegetation cover and species richness after recurrent forest fires in the Eastern Mediterranean ecosystem of Mount Carmel, Israel. *Science of the Total Environment*, 572, 1395-1402.
- Trambly, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S. M., Volaire, F., Boone, A., Le Page, M., Llasat, M. C., Albergel, C., Burak, S., Cailleret, M., Kalin, K. C., Davi, H., Dupuy, J. L., Greve, P., Grillakis, M., Hanich, L., Jarlan, L., Martin-StPaul, N., ... & Polcher, J. (2020).

REFERENCES

Challenges for drought assessment in the Mediterranean region under future climate scenarios. *Earth-Science Reviews*, 210, 103348.

- Turco, M., Llasat, M. C., von Hardenberg, J., & Provenzale, A. (2013). Impact of climate variability on summer fires in a Mediterranean environment (northeastern Iberian Peninsula). *Climatic Change*, 116(3), 665-678.
- Turco, M., Llasat, M. C., von Hardenberg, J., & Provenzale, A. (2014). Climate change and wildfires in the Mediterranean region: A review. *Regional Environmental Change*, 14(5), 1679-1693.
- Turco, M., Rosa-Cánovas, J. J., Bedia, J., Jerez, S., Montávez, J. P., Llasat, M. C., & Provenzale, A. (2018). Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nature Communications*, 9(1), 3821.
- Turco, M., von Hardenberg, J., AghaKouchak, A., Llasat, M. C., Provenzale, A., & Trigo, R. M. (2016). On the key role of droughts in the dynamics of summer fires in Mediterranean Europe. *Scientific Reports*, 6(1), 1-10.
- Underwood, E. C., Viers, J. H., Klausmeyer, K. R., Cox, R. L., & Shaw, M. R. (2009). Threats and biodiversity in the Mediterranean biome. *Diversity and Distributions*, 15(2), 188-197.
- Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, 23(7), 1696-1718.
- Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Beguería, S., Trigo, R., López-Moreno, J. I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., & Sanchez-Lorenzo, A. (2013). Response of vegetation to drought time-scales across global land biomes. *Proceedings of the National Academy of Sciences*, 110(1), 52-57.
- Vicente-Serrano, S. M., Lopez-Moreno, J. I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., & Espejo, F. (2014). Evidence of increasing drought severity caused by temperature rise in southern Europe. *Environmental Research Letters*, 9(4), 044001.
- Vilar, L., Garrido, J., Echavarría, P., Martínez-Vega, J., & Martín, M. P. (2016). Comparative analysis of CORINE and climate change initiative land cover maps in Europe: Implications for wildfire occurrence estimation at regional and local scales. *International Journal of Applied Earth Observation and Geoinformation*, 44, 53-65.
- Zeroual, A., Assani, A.A., Meddi, M. et al. (2019). Assessment of climate change in Algeria from 1951 to 2098 using the Köppen–Geiger climate classification scheme. *Clim Dyn* 52, 227–243. <https://doi.org/10.1007/s00382-018-4128-0>